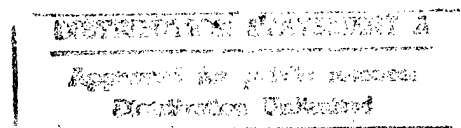# NATIONAL COMMUNICATIONS SYSTEM

TECHNICAL INFORMATION BULLETIN 92-20

EVALUATION OF ADVANCED METEOR BURST COMMUNICATION TECHNIQUES

DECEMBER 1992

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
**701 SOUTH COURT HOUSE ROAD
ARLINGTON, VA 22204-2198**

19970117 045

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1992	Final Report

4. TITLE AND SUBTITLE
Evaluation of Advanced Meteor Burst Communication Techniques

5. FUNDING NUMBERS
DCA100-91-C-0032

6. AUTHOR(S)
Robert Fenichel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025-3493

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Communications System
Office of Technology and Standards Division
701 South Court House Road
Arlington, Virginia 22204-2198

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NCS TIB 92-20

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes the results of a study to define a baseline advanced Meteor-Burst Communication (MBC) system that can serve as a step along the way to developing new Federl Standards for a system of this type. Five technology areas have been evaluated in this study: advanced modulations, including error-correcting codes; adaptive data rates; adaptive antennas; network topology and routing; and mobile systems. The recommended modulation for advanced MBC systems in adaptive trellis-coded moduältion (TCM) using M-ary PSK with convolutional coding for error correction. The recommended antennas are adaptive in beam forming, nulling, and polarization. For MBC systems that consist of multiple sites, modern networking techniques are recommended, including adaptive routing capabilities. Finally, a program plan is suggested for establishing a baseline version of an MBC system with these advanced technologies. This baseline system must be tested to demonstrate the feasibility of the concepts and to gather performance data that can help define the new Federal standards that will permit the orderly development of the next generation of MBC systems.

14. SUBJECT TERMS
Error-Correcting Codes, Mobile Systems
Meteor-Burst Communication (MBC) Systems
Digital Signal Processing (DSP)

15. NUMBER OF PAGES
90

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASS	UNCLASS	UNCLASS	UNLIMITED

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to *stay within the lines* to meet *optical scanning requirements.*

Block 1. Agency Use Only *(Leave blank).*

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C	-	Contract	PR	- Project
G	-	Grant	TA	- Task
PE	-	Program Element	WU	- Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

DOD	-	See DoDD 5230.24, "Distribution Statements on Technical Documents."
DOE	-	See authorities.
NASA	-	See Handbook NHB 2200.2.
NTIS	-	Leave blank.

Block 12b. Distribution Code.

DOD	-	Leave blank.
DOE	-	Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
NASA	-	Leave blank.
NTIS	-	Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

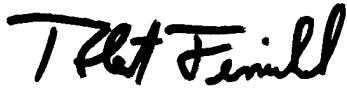**Block 16.** Price Code. Enter appropriate price code *(NTIS only).*

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.
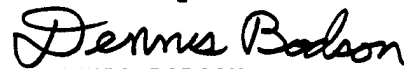
EVALUATION OF ADVANCED METEOR BURST COMMUNICATION TECHNIQUES

PROJECT OFFICER

[signature]

ROBERT FENICHEL
Electronics Engineer
Office of Technology
 and Standards

APPROVED FOR PUBLICATION:

[signature]

DENNIS BODSON
Assistant Manager
Office of Technology
 and Standards

FOREWORD

Among the responsibilities assigned to the Office of the Manager, National Communications System, is the management of the Federal Telecommunication Standards Program. Under this program, the NCS, with the assistance of the Federal Telecommunication Standards Committee, identifies, develops, and coordinates proposed Federal Standards that either contribute to the interoperability of functionally similar Federal telecommunication systems or to the achievement of a compatible and efficient interface between computer and telecommunication systems. This Technical Information Bulletin discusses potential topics that may be in an advanced Meteor Burst Communication (MBC) standard, developing MBC into a more advanced, useful, and beneficial means of communication.

Comments on this TIB are welcome and should be addressed to:

Office of the Manager
National Communications System
Attn: NT
701 S. Court House Road
Arlington, VA 22204-2198
Telephone (703) 692-2124

SRI International

Final Report • December 1992

EVALUATION OF ADVANCED METEOR BURST COMMUNICATIONS

Prepared for:

Office of the Manager
National Communications System
701 S. Courthouse Road
Arlington, VA 22204-2199

Contract DCA100-91-C-0032

SRI Project 3427, Delivery Order 0011, CDRL Item 006
SRI Project 3592, Delivery Order 0012, CDRL Item 006

ABSTRACT

Meteor-burst communication (MBC) systems are an attractive option for a number of possible civilian and military applications that require independent, reliable, and secure, but relatively low-data-rate, communication channels between sites that are separated by distances from about 200 to 2000 km. Although MBC systems have been in use for many years, a number of opportunities now exist for incorporating advanced technologies to improve the performance of the next generation of MBC systems. This report describes the results of a study to define a baseline advanced MBC system that can serve as a step along the way to developing new Federal Standards for a system of this type. Five technology areas have been evaluated in this study: advanced modulations, including error-correcting codes; adaptive data rates; adaptive antennas; network topology and routing; and mobile systems. The recommended modulation for advanced MBC systems is adaptive trellis-coded modulation (TCM) using M-ary PSK with convolutional coding for error correction. The recommended antennas are adaptive in beam forming, nulling, and polarization. For MBC systems that consist of multiple sites, modern networking techniques are recommended, including adaptive routing capabilities. Finally, a program plan is suggested for establishing a baseline version of an MBC system with these advanced technologies. This baseline system must be tested to demonstrate the feasibility of the concepts and to gather performance data that can help define the new Federal standards that will permit the orderly development of the next generation of MBC systems.

CONTENTS

ILLUSTRATIONS

TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ACK   Acknowledgment (i.e., of receipt of a message)

ADC   Analog-to-digital converter

ADR   Adaptive data rate

AGC   Automatic gain control

ARQ   Automated repeat query

ASC   Adaptive symbol constellation

ASR   Adaptive symbol rate

ATCM   Adaptive trellis-coded modulation

BCH   Bose-Chaudhuri-Hocquenghem (codes)

BER   Bit error rate

BERA   Block-error-rate adapting (method)

BFSK   Binary frequency shift keying

BPSK   Binary phase shift keying

b/s   Bits per second

b/s/Hz   Bits per second per hertz

CCRA   Channel-capacity-rate adapting (method)

CPU   Central processing unit

CW   Continuous wave

DAC   Digital-to-analog converter

dB   decibel

dBHz   decibel relative to a hertz

dBi   decibel relative to an isotrope

dBW/Hz   decibel relative to watts per hertz

DBPSK   Differential binary phase shift keying

DCT   Destination address count

DoD   Department of Defense

DSP   Digital signal processing

EACK	End-to-end acknowledgment
e.g.	Exempla gratia (for example)
ENAK	End-to-end negative acknowledgment
et al.	Et alii (masculine) or et alia (neuter), and others
FAVR	Feedback-adaptive variable rate
FEC	Forward error correction
FIR	Finite impulse response
FSK	Frequency shift keying
FTP	File transfer protocol
GMSK	Gaussian minimum shift keying
GPS	Global positioning system
I&Q	In-phase and quadrature (for sampling)
IP	Internet protocol
IPC	Interprocess communication
ITT	International Telephone and Telegraph
kb/s	kilobits per second
kHz	kilohertz
km	kilometers
km/s	kilometers per second
knots	nautical miles per hour
ks/s	kilosymbols per second
kW	kilowatts
LAN	Local area network
LORAN	Long range navigation system
LSC	Last segment count
MATLAB	Matrix laboratory
MBC	Meteor-burst communication
MCC	Meteor Communication Corporation

ms	milliseconds
MSK	Minimum shift keying
MTC	Message type code
μs	microseconds
NACK	Negative acknowledgment (see ACK)
NTIA	National Telecommunications and Information Administration
NCCOSC	Naval Command and Control and Ocean Surveillance Center
NESEA	Naval Electronics Systems Engineering Activity
NRL	Naval Research Laboratory
NRZ	Non return to zero
OQPSK	Offset quadrature phase-shift keying
OSI	Open system interconnect
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RDP	Reliable datagram protocol
RF	Radio frequency
RPC	Remote procedure call
RS	Reed-Solomon (codes)
s	seconds
SAIC	Science Applications International Corporation
SHAPE	Supreme Headquarters Allied Powers Europe
SICBM	Small intercontinental ballistic missile
SINCGARS	Single channel ground-airborne radio subsystem
SNOTEL	Snowpack telemetry
SNR	Signal-to-noise ratio
SPAWAR	Space and Naval Warfare Systems Command
SRI	SRI International, Menlo Park, CA

TCM	Trellis-coded modulation
TCP	Transmission control protocol
UDP	Unreliable data protocol
UTC	Coordinated universal time
VMTP	Versatile massage transaction protocol
W	watts

1 INTRODUCTION

Meteor-burst communication (MBC) systems are an attractive option for a number of possible civilian and military applications that require independent, reliable, and secure communication channels between sites that are separated by distances from about 200 to 2000 km and for which a relatively low data rate is adequate. Although MBC systems have been in use for many years, a number of opportunities now exist for incorporating advanced technologies to improve the performance of the next generation of these systems. The recent and ongoing revolution in digital signal processing (DSP) capabilities now permits the practical implementation of these advanced technologies. In particular, high-speed microprocessors now can perform the necessary DSP in real time to improve the link margins and increase the throughput of MBC systems in a manner that is both cost effective and highly reliable. This report describes the results of a study for the Office of the Manager, National Communications System, to define a baseline advanced MBC system that can serve as a step along the way to developing new Federal standards for a system of this type.

Proposed Federal Standards 1055, 1056, and 1057 have already been prepared in draft form to apply to the current generation of MBC systems that use conventional technology. However, before similar standards can be proposed for an advanced MBC system, it is necessary to characterize, evaluate, and test various candidate techniques that have the potential for substantially improving the performance of the new system.

Section 2 of this report describes our approach to this problem, which consisted of contacting commercial and government-funded organizations with relevant expertise and surveying the available literature to identify the most promising technologies. We also developed a new model based on actual MBC data to use in evaluating the relative merits of these technologies. Section 3 presents the results of this evaluation. The particular technology areas evaluated are: advanced modulations (including error-correcting codes); adaptive data rates; adaptive antennas; network topology and routing; and mobile systems. Section 4 then applies the results of our observations to derive the specifications for the prototype of an advanced MBC system. This prototype is designed to run as an experimental system to collect the test data needed to demonstrate the feasibility of the design concept and to quantify the performance improvement achievable with the particular implementation of advanced technologies. Finally, Section 5 presents a suggested program plan for building this prototype system, performing the necessary field tests, and using the results to write the first draft of the new proposed standards for an advanced MBC system.

This document constitutes the final reports for Delivery Orders 0011 and 0012 on Contract DCA100-91-C-0032. The final reports on these two Delivery Orders have been combined into a single document to provide the reader with a comprehensive description of the overall effort, which is logically a single integrated package. However, the contractually separate portions of the work can be identified as follows. Part I involved four tasks: Identification of Advanced MBC Techniques (Task 1); Advanced Modulations (Task 2); Adaptive Data Rate Modems (Task 3); and MBC System Baseline (Task 4). Part II involved four tasks: Adaptive Antennas (Task 1); Network Topology and Routing (Task 2); Mobile Communications (Task 3); and MBC System Baseline (Task 4). Portions of this report (dealing with networking and with mobile systems) were previously published as an interim report, but they are repeated here for the convenience of the reader.

This study was carried out over the period from 8 April 1992 to 30 November 1992.

1

2 METHODOLOGY

The purpose of this study is to define the baseline characteristics of an advanced MBC system that can be used in developing a new Federal standard for systems of this sort. Our approach to this task is to identify candidate advanced technologies, to develop an appropriate model for the evaluation of these technologies, to perform the evaluation, and to apply the results to the definition of the baseline system.

2.1 Identification of Advanced Technologies

Our approach to this task has been first to contact the various members of the MBC community, including commercial firms in the business of selling MBC systems, organizations that do research in the field, and government offices that have supported the research or procured MBC systems, and second to review the available publications that deal with the subject. We have contacted the following commercial firms: Meteor Communications Corporation (MCC) in Kent, Washington; BroadCom Inc. in Mahway, New Jersey; Westinghouse Electric Corporation in Hanover, Maryland; M2 Enterprises in Fresno, California; MAR Inc. in Arlington, Virginia; and International Telephone and Telegraph (ITT) in Ft. Wayne, Indiana. Research organizations include: Science Applications International Corporation in Stow, Massachusetts; Lowell University in Lowell, Massachusetts; and Rutherford-Appleton Laboratory in the United Kingdom. Government organizations include: Defense Advanced Research Projects Agency; U.S. Air Force, Electronic Systems Division, Rome Laboratories; U.S. Navy, Naval Electronics Systems Engineering Activity (NESEA), Naval Command and Control and Ocean Surveillance Center (NCCOSC), Space and Naval Warfare Systems Command (SPAWAR), and the Naval Research Laboratory; National Telecommunications and Information Administration (NTIA); and Supreme Headquarters Allied Powers Europe (SHAPE) Technical Center.

The results of our literature review are reflected in the references listed at the end of this report. Where appropriate, we have identified the intellectual property rights associated with particular advanced techniques developed for MBC applications.

The following technology areas have been identified as potentially the most important for the next generation of MBC systems: advanced modulations; adaptive data rates; adaptive antennas; networking; and mobile systems. These technologies are discussed in detail and evaluated in Section 3 of this report. However, a few introductory comments are included here to set the stage for the later detailed discussions.

For advanced modulations, we have considered well-established technologies that have been in use in existing systems for several years, emerging technologies that have begun to appear more recently, and future technologies that have been proposed or have to date been tested with experimental MBC systems only.

For adaptive data rates, we have likewise considered established ideas such as those described by Abel (1986) and Larsen et al. (1990), which employ data rates that can be adjusted for different meteor trails but are fixed for a given trail, or can be continuously varied throughout each trail. We have identified a number of emerging technologies such as feedback adaptive variable bit rate (Schilling et al., 1991; Chang and Schilling, 1992), adaptive symbol rate (Braun and Meyerowitz, 1991), and adaptive coding (Pursley and Sandberg, 1992). Also, we have identified attractive

possible future technologies, such as trellis-coded modulation combined with three PSK signal sets as presented by Jacobsmeyer (1992).

For adaptive antennas, attractive options that have been identified are: arrays with multiple fixed beams; retrodirective antennas; and arrays with adaptive digital beamforming, nulling, and polarization-control capabilities.

For networking, we have evaluated various routing strategies through an array of multiply connected sites to find the one with the greatest potential payoff in terms of increased through-put. Existing MBC networks, such as SNOTEL and the Alaska MBC System (Kokjer and Roberts, 1986), are simple star networks in which a master station collects environmental data from multiple remote stations, but these systems typically have such limited data-rate requirements that increased throughput is not a particularly relevant issue. However, as discussed in Section 3.4, modern networking technologies can significantly improve the performance of systems with more-sophisticated multiple stations, each of which can be linked to more than one other station.

For mobile systems, the primary opportunities will be in the practical (small, lightweight, low-power) implementation of the other advanced technologies identified above, especially the advanced modulations and the adaptive data rates.

2.2 Model for Technology Evaluation

Existing MBC models are concerned with calculating the expected performance of a given system under a particular set of circumstances in terms of such output quantities as signal-to-noise-ratio (SNR), average duration of meteor trails, and average time interval between trails. The systems are specified by such quantities as operating frequency, transmitter power, antenna gains, and bandwidth. The operating circumstances are defined by site locations, time of day, and time of year. A convenient overview description of these models can be found in Schanker (1990). These models are quite good for their intended purposes of system design, performance prediction and evaluation, and even for controlling system parameters (such as antenna steer direction) in real time during operations to adjust for well-known, long-term statistical properties of meteor trails (SAIC, 1992). However, these models are not suited for some of the purposes of this study, especially the evaluation of various modulation and coding techniques. For this reason, we have developed an empirical model based on an extensive database of experimental MBC signals recorded previously by SRI for another program (Heilman et al., 1989; Rich et al., 1990).

The SRI MBC channel model is based on actual field measurements recorded during a 5-month period from the fall of 1988 to the spring of 1989. Because these data were collected to investigate the throughput of a possible MBC system to be used to communicate between hardened mobile launchers of small intercontinental ballistic missiles (SICBMs) and the launch control center, they were collected with a large number of sites in the vicinity of the Minuteman wing in northern Montana. However, these data are representative of conditions on typical mid-latitude paths. The data were recorded using receivers with custom vector demodulators to sample the quadrature detected signals. In-phase and quadrature (I&Q) sampling at 20 kilosymbols per second (ks/s) with 12 bits of resolution was used to define the signal variations with time.

Figure 2-1 shows the process by which we developed the SRI MBC channel model. The process starts with the raw I&Q data that were processed to display trail amplitude and thus to

3

809-1
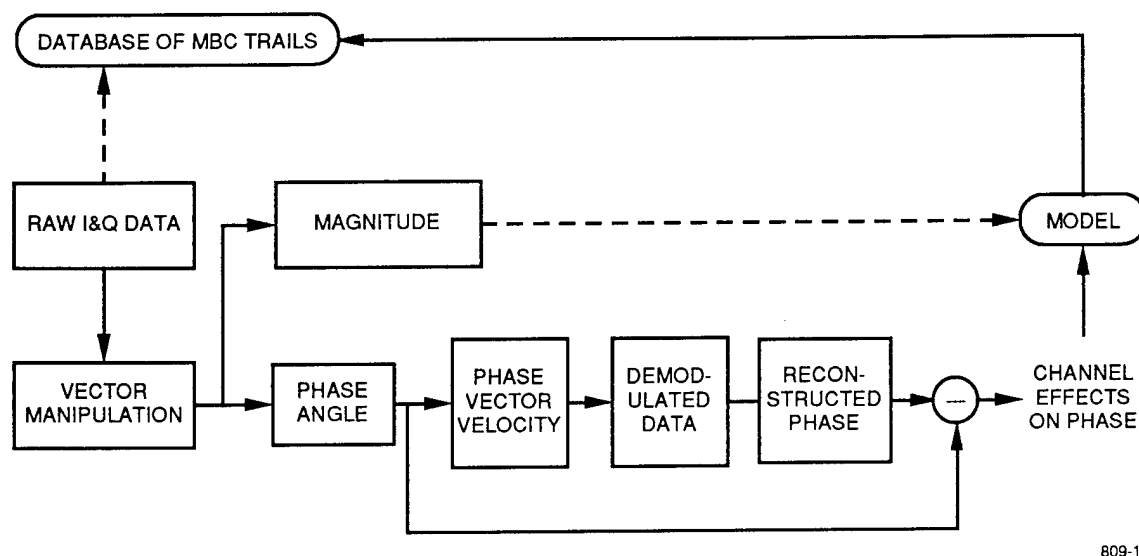
FIGURE 2-1   SRI MBC CHANNEL MODEL DEVELOPMENT PROCESS

permit each trail to be assigned to one of five types (to be discussed below). The raw I&Q data were converted to a format that could be used by Matlab, a commercial mathematical simulation software package from MathWorks, Inc. in Sherborn, MA. For each trail, the time history of the magnitude was extracted and included directly in the model, whereas the phase angles had to be extracted and unwrapped.

Figure 2-2 is an example of an unwrapped phase angle for one trail. Because frequency shift keyed (FSK) modulation was used for the signal, two distinct slopes can be seen in the raw phase-angle data, representing the two distinct rates of rotation of the phase vector. From this information, the phase vector velocities, or slopes, were defined, representing the mark and space frequencies of the transmission. The data were then demodulated based on these two phase velocity vectors, and the result was used to reconstruct the true phase vector.

Figure 2-3 shows the demodulated data as a solid line along with the reconstructed phase as a dashed line for this same data example. As indicated in Figure 2-1, the reconstructed phase was compared with the phase of the raw data to define the effects of the meteor burst channel on phase variations for the duration of the trail. These phase effects, combined with the amplitude effects, then make up the basis of the model. As shown in Figure 2-1, the phase and amplitude histories for each trail are included in the database along with the raw data. Other information also included in the database for each trail includes date and time of occurrence, classification, duration, maximum amplitude, and number of points.

Figure 2-4 shows an example of the resulting magnitude and phase effects for a typical underdense trail included in the database. As expected, in the usable part of the trail where the signal-to-noise-ratio is higher, phase effects are constant and relatively small. The phase is significant only during portions of the trail when the SNR is high. The slope when the SNR drops off is a consequence of the phase calculation process and is insignificant.

4
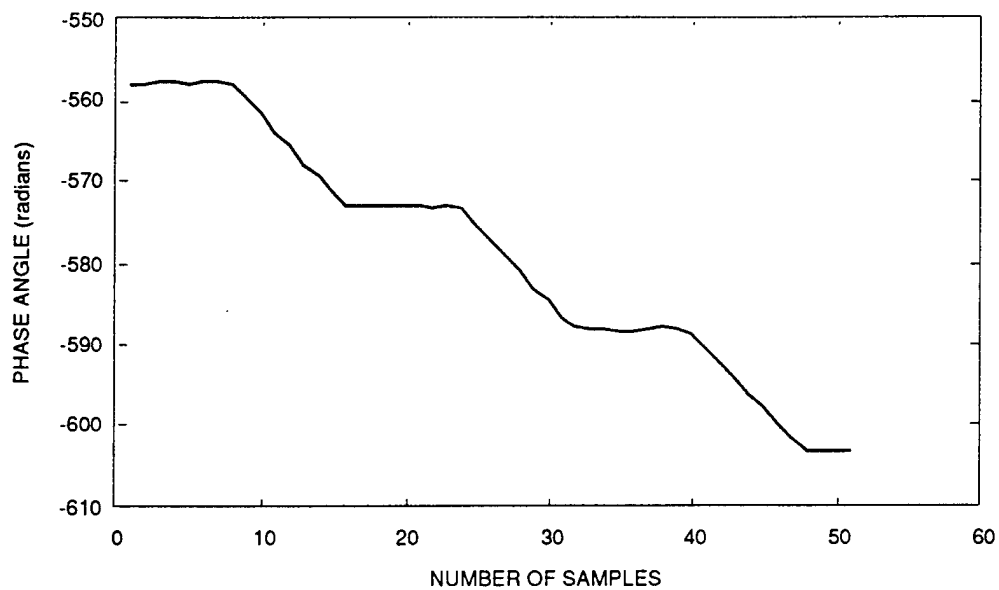
FIGURE 2-2   EXAMPLE OF UNWRAPPED PHASE ANGLE
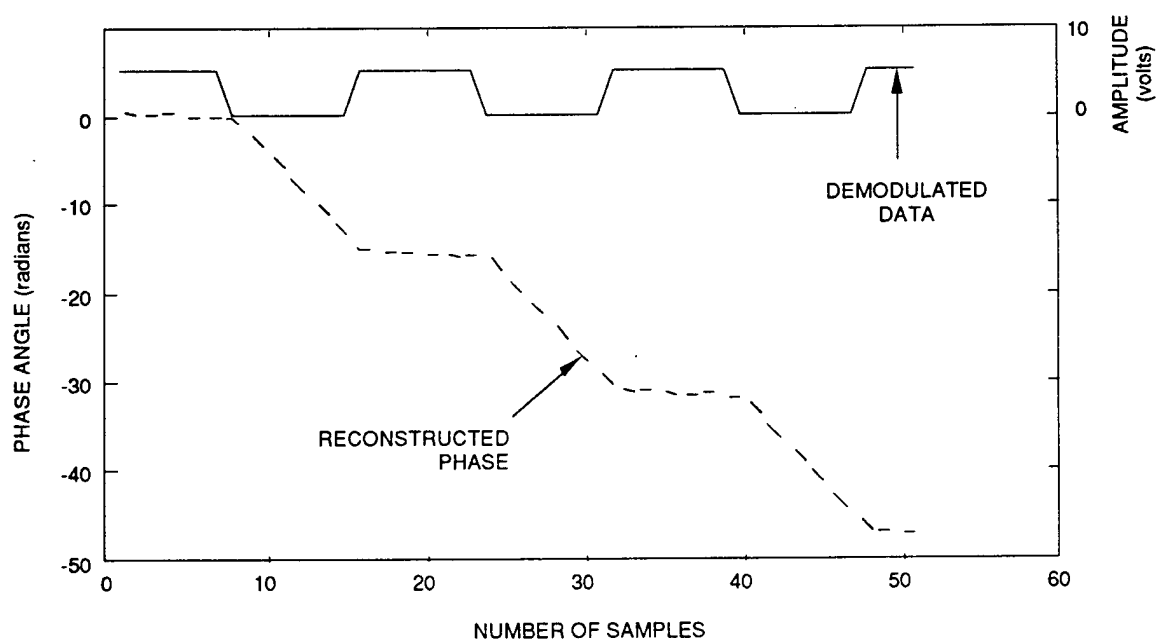
FIGURE 2-3   DEMODULATED DATA AND RECONSTRUCTED PHASE

5
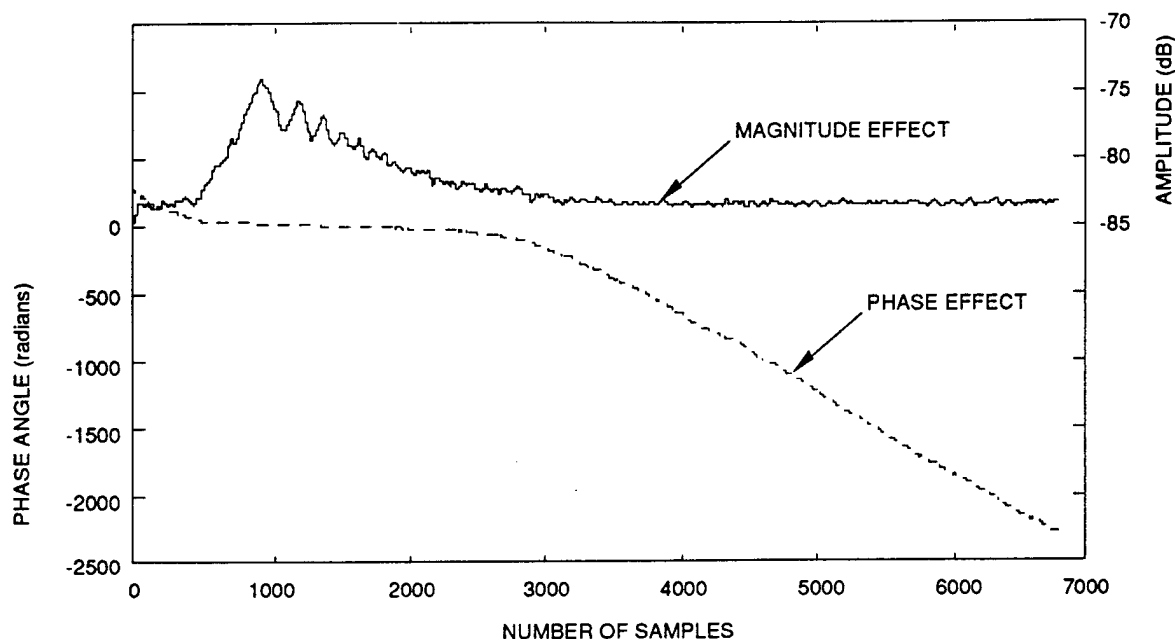
FIGURE 2-4   EXAMPLE OF CHANNEL EFFECTS ON MBC SIGNALS

Figure 2-4 shows an example of the resulting magnitude and phase effects for a typical underdense trail included in the database. As expected, in the usable part of the trail where the signal-to-noise-ratio is higher, phase effects are constant and relatively small. The phase is significant only during portions of the trail when the SNR is high. The slope when the SNR drops off is a consequence of the phase calculation process and is insignificant.

On the basis of their amplitude characteristics as a function of time, the meteor trails in the database were divided into the five categories described below and illustrated in Figure 2-5. These categories and their occurrence statistics will be used for evaluating the performance of various advanced MBC technologies:

Underdense trails that have the classical abrupt rise and relatively long exponential decay.

Overdense trails that have a rise time that may be either short or long, but are relatively flat across the top, and have a convex, nonexponential decay.

Underdense trails with overdense characteristics that have short rise times and slow exponential decays, but are relatively flat across the top and may show fading.

Overdense trails with fading that causes the signal to rise and fall repeatedly, usually returning to the maximum or near-maximum amplitude after the period of fading.

Nonspecular trails that are overdense in nature with fade-like sidelobes on both sides of the peak amplitude of the trail.

6
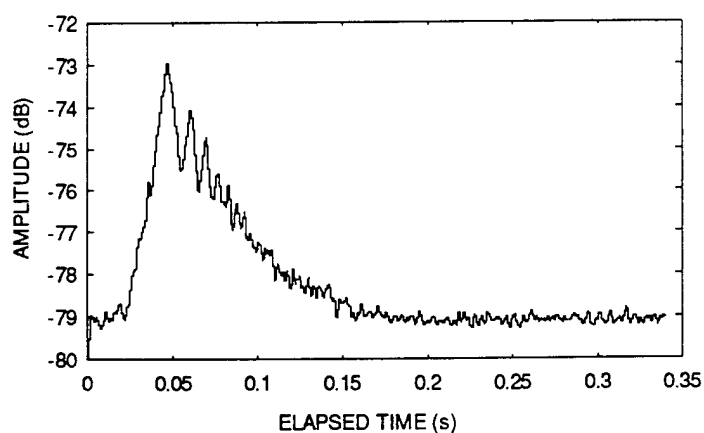
(a) Underdense Trail
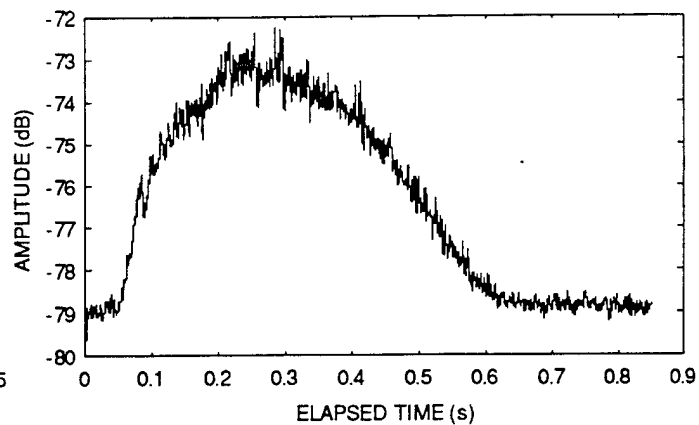
(b) Overdense Trail
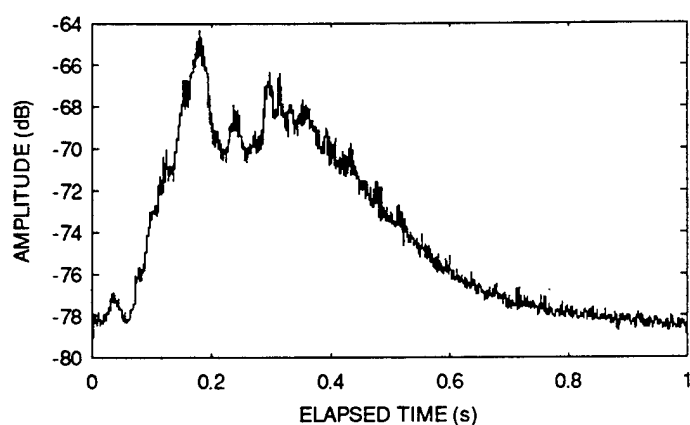
(c) Underdense Trail With Overdense Characteristics
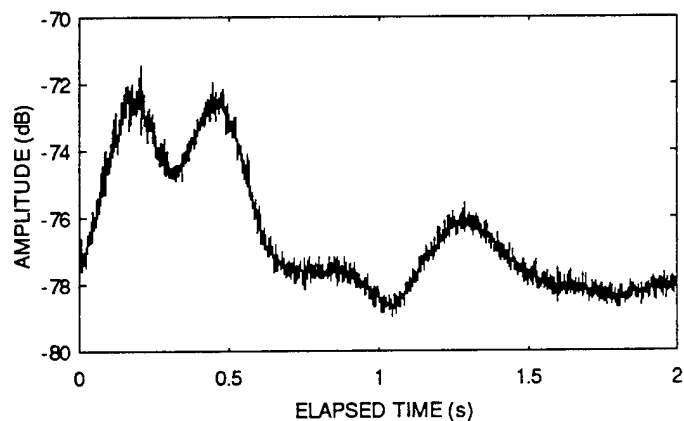
(d) Overdense Trail With Fading
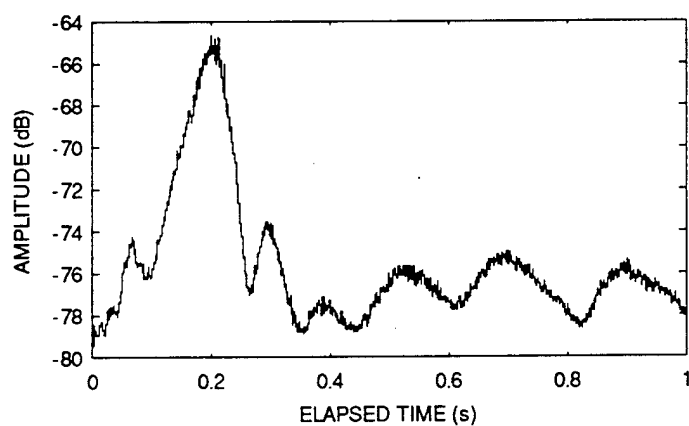
(e) Nonspecular Trail

809-5

FIGURE 2-5   ILLUSTRATIONS OF CATEGORIES OF METEOR TRAILS IN THE SRI MBC MODEL

7

The relative frequency of occurrence of these different types of trails, as derived from the experimental data, are given in Table 2-1. As can be seen in this table, the majority of the trails (59%) are of the classical underdense variety (as would be expected), whereas all of the other four trail types occur much less frequently. These occurrence statistics are used as weighting factors in the analysis of the relative throughputs of various advanced modulations and adaptive data rate techniques as described in Section 3.

One minor limitation of the SRI MBC model should be noted. It is based on experimental data with a bandwidth of only 10 kHz. However, this limitation should not be significant so long as MBC systems are restricted by the present bandwidth allocations by the Federal Communications Commission (FCC) of 20-kHz channel separation and 16-kHz usable bandwidth.

Table 2-1

OBSERVED DISTRIBUTION OF METEOR TRAIL TYPES

Trail Type	Frequency of Occurrence (Percent)
Underdense	59
Overdense	17
Underdense with overdense characteristics	12
Overdense with fading	4
Nonspecular	8

2.3 Definition of Baseline System

A detailed description of the baseline system, which is the primary product of this study, is presented in Section 4. However, a general discussion of the system is provided here to highlight its importance and to explain the rationale for the features it contains.

The primary difficulty in designing a baseline system is that its particular application is undefined, so that there is no way of knowing how many sites will be needed, how much data throughput will be required over the links between the different sites, and what will be the nature of the physical, economic, and regulatory constraints that will force unique design tradeoffs to be made in each case. Therefore, we have taken the approach that anything that increases throughput is desirable, but only so long as the improved performance is the result of the application of advanced digital signal processing techniques and not simply achieved by brute-force methods such as increased transmitter power or larger antenna apertures. Whenever possible, we have taken a modular approach to the design, so that the system can be scaled up or down as may be appropriate in any given situation.

Also, we assume that two different generic types of systems will be needed, and these are referred to as master stations and remote stations. Master stations are assumed to have less severe limitations on power and antenna size, and they are assumed to be required to communicate with

8

both remote stations and other master stations, and probably with several of each type that may be located in any direction (thus requiring azimuthally omnidirectional antenna coverage). Because of the increased power-aperture product available at master stations, they can communicate with each other at much higher data rates than they can use in communicating with remote stations. Remote stations are assumed to have relatively small amounts of prime power available and to be limited to relatively low gain antennas. The remote antennas must have the omnidirectional coverage needed to link to several different master stations that may be in located in arbitrary directions. Remote stations are assumed not to be able to communicate directly with other remotes (because of their limited power-aperture product), but to be able to be linked to any of them via master stations. For purposes of cost tradeoff analysis, master stations are assumed to cost ten times as much as remote stations.

3 TECHNOLOGY EVALUATIONS

As noted in Section 2, several different technology areas have been identified as being highly promising for an advanced MBC system. None of these areas involve the basic RF technologies of the system such as transmitters, receivers, or antenna elements. Instead, all are concerned primarily with the application of modern DSP techniques to improve system performance. This emphasis on DSP does not mean that analog techniques may not be considered for implementing the advanced technologies in specific cases. This section presents evaluations of the candidate technology areas, and these evaluations lead to the selection of the particular techniques recommended for the prototype baseline system to be described in Section 4.

3.1 Advanced Modulations

Modulations currently in use in the MBC industry include binary frequency shift keying (BFSK), binary phase shift keying (BPSK), differential binary phase shift keying (DBPSK), and minimum shift keying (MSK). Additional modulations that we have identified as promising because of their success in other communication fields are: gaussian minimum shift keying (GMSK), which is currently the standard for the European GSM digital cellular telephone; quadrature amplitude modulation (QAM), which is used in satellite communications; and trellis-coded modulation (TCM), which has been applied in the CCITT v.32 standard, 9600-b/s voice-band modem.

In our evaluation of these modulations, we assumed in accordance with the National Telecommunications and Information Administration (NTIA) guidelines (Cohen et al.,1989), that the channel is limited to 16 kHz necessary bandwidth with 20-kHz channel spacing. Thus, bandwidth-efficient modulations are especially important. The basic criterion for comparing one modulation to another is relative throughput—that is, the total number of bits that can be communicated in a given time by one modulation compared with another. The time period must be long enough to include numerous meteor trails of all types, and is typically a few hours in duration. Related to throughput is bit error rate (BER), but BER has not been calculated explicitly in the simulations of system performance given here. In addition to throughput, secondary criteria used here in evaluating modulations are cost and the risk associated with the technical complexity of implementation in an operational system. In our model, we use a database of nearly an hour of continuous trails, with no waiting time between trails as would occur in any actual system. Eventually, the effect of the distribution of waiting times between different trails should be included in the model, but to date this has not been done.

To measure the relative throughput of different modulations, we used the channel model described in Section 2.2 to define the variation of amplitude and phase of the meteor burst signals as a function of time. The modulations and the effects of the model were calculated using Matlab. The process of simulating a modulation involved three steps: creating a Matlab model of the modulator and demodulator; running the modulation through the channel model; and calculating throughput. Transmitter power and channel bandwidth were assumed to be the same in all cases, and we implemented automatic gain control (AGC) and carrier recovery when needed. Figure 3-1 shows how the five types of meteor burst signals (referred to here as trails) were used in the model.

A more detailed view of the simulation process is shown in Figure 3-2. Using Matlab, we modulated the signal and passed it through one of the representative trails by multiplying the
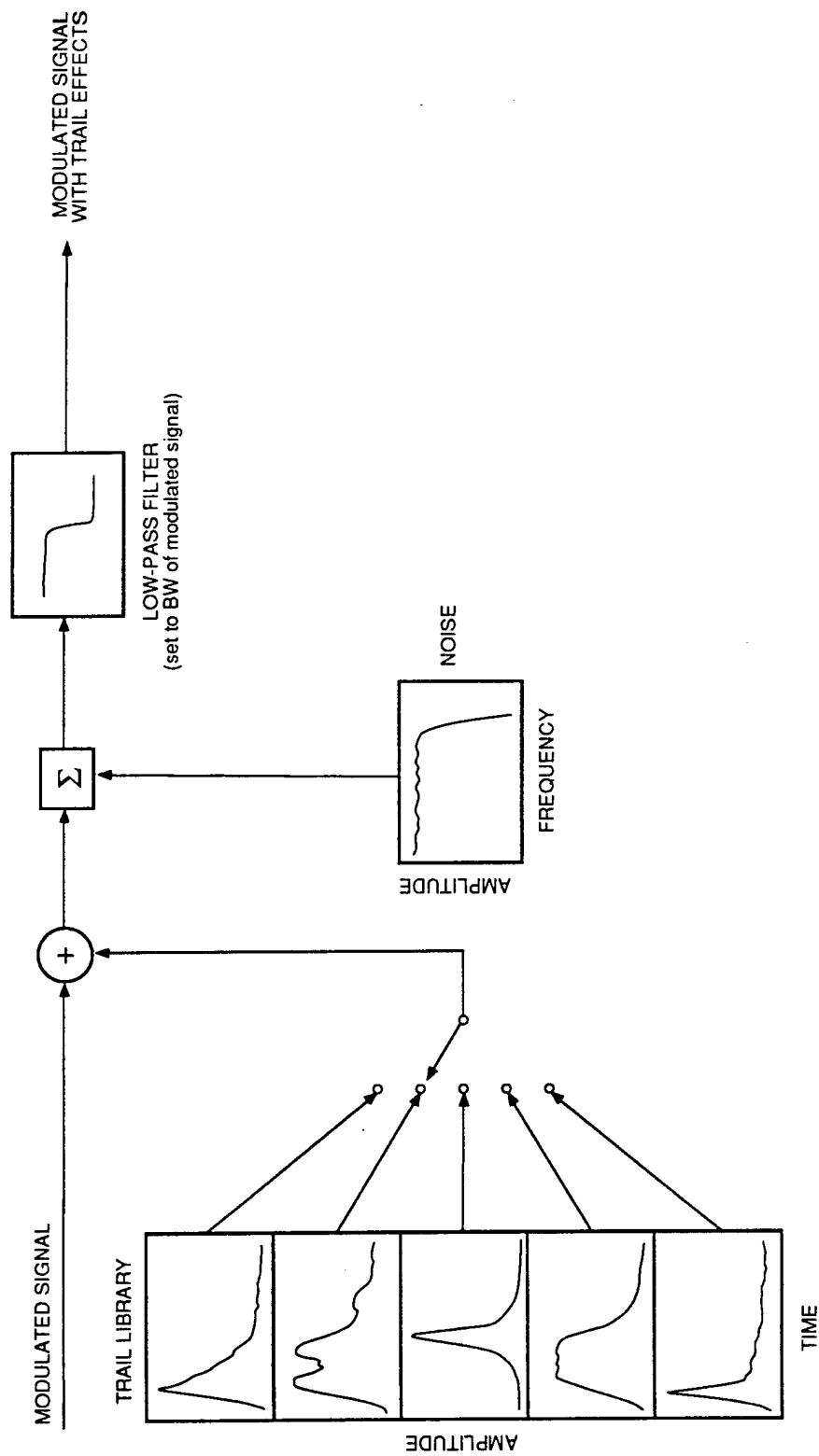
FIGURE 3-1   SCHEMATIC ILLUSTRATION OF THE CHANNEL MODEL
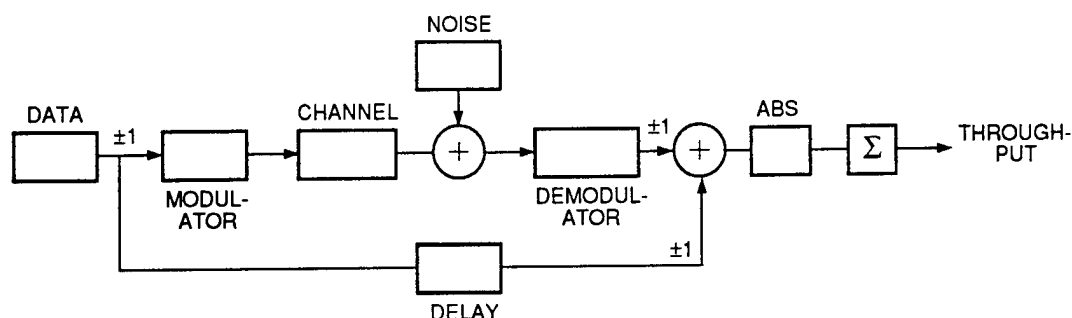
11

FIGURE 3-2 METHOD OF THROUGHPUT CALCULATION

complex modulated vector by the complex vector representing the phase and amplitude variations of the trail. To offset the effect of having filtered the data, we then added band-limited white Gaussian noise (to simulate galactic and thermal noise) and demodulated the signal to reconstruct the transmitted data. We compared the original and received data to find out how many correct bits were received. This procedure was repeated separately for each trail, using the same noise and data vectors in each case. A set of five throughput values was thus calculated for each modulation.

The final throughput was calculated by assigning a weight to each value depending on the frequency of occurrence of that type of trail (as defined by the model) and summing the results. This result is a relative measure for comparison purposes only. It does not correspond to the BER or throughput of an actual MBC system, which of course would depend on other factors such as antenna gain and receiver sensitivity.

3.1.1 Descriptions of Modulations

Binary frequency shift keying (BFSK) is considered a simple modulation because no carrier recovery is needed and it does not require a coherent receiver. The signal is modulated by switching between two different frequencies. Typically the higher frequency represents a mark or *1* and the lower frequency represents a space or a *0*, as shown in Figure 3-3. BFSK has a constant
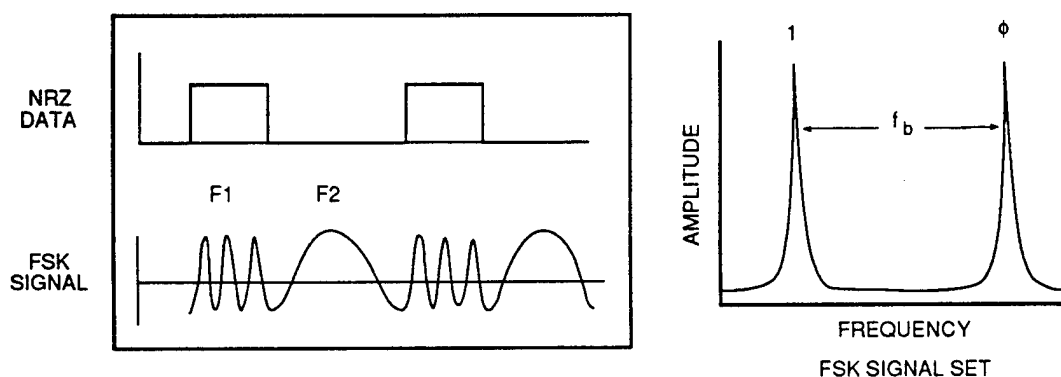
FIGURE 3-3 BFSK MODULATION

12

envelope, so is not affected by nonlinearities in the channel or transceiver equipment. The frequency separation of the two frequencies must make them orthogonal. In the general BFSK case, orthogonality means the frequencies must be separated by the bit rate (1/T) in hertz where T is the symbol period. (For BFSK there is only 1 bit per symbol.) The bandwidth efficiency of this modulation is a little less than 1 bit per second per hertz (b/s/Hz), so it is one of the least spectrally efficient modulations. BFSK is the Bell 212A standard for 300 b/s voice-band modem communication. A BFSK modulator can be implemented so that the modulated signal has constant phase (using a voltage controlled oscillator, for example).

Minimum shift keying (MSK) can be considered a special case of FSK with a frequency separation 1/(2T) that is half of that for BFSK (as shown in Figure 3-4). It can also be described as a variation of offset quadrature phase-shift keying (OQPSK) with a modulating data pulse that is sinusoidal rather than rectangular (Pasupathy, 1979). MSK is spectrally more efficient than BFSK because of the smaller frequency separation and, like BFSK, it has a constant envelope and constant phase. MSK is usually demodulated with a coherent receiver to achieve the best performance.
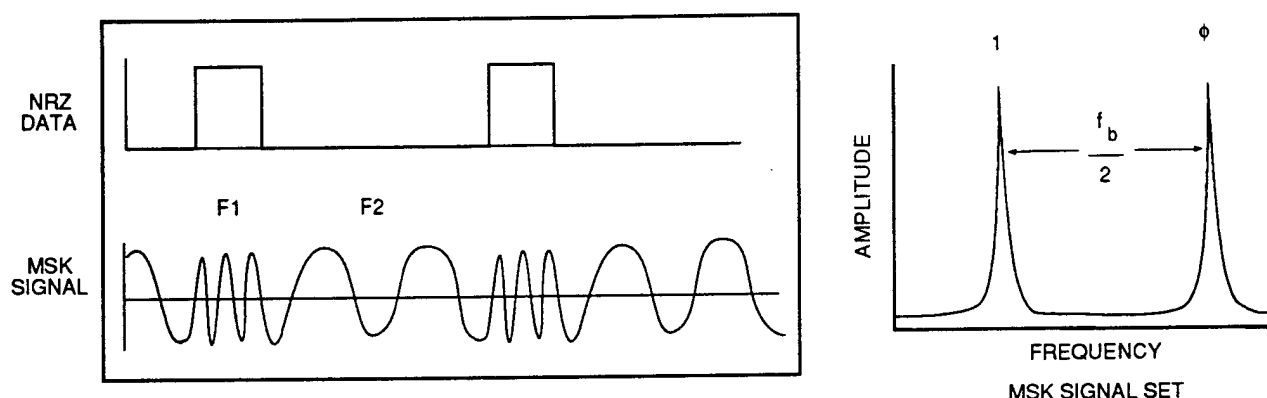
FIGURE 3-4 MSK MODULATION

Gaussian minimum shift keying (GMSK) is a variation on MSK that uses a gaussian-shaped premodulation filter. With this filter, changes in the modulated data stream are less abrupt than for MSK, which reduces the sidelobes in the final spectrum of the modulated signal. The result is reduced interchannel interference, but the penalty is that the SNR for GMSK must be about 0.7 dB higher than for MSK to achieve the same BER (Murota and Hirade, 1981). However, an MSK receiver can be used to demodulate a GMSK signal.

M-ary FSK/MSK uses multiple (m-ary) frequencies to represent multiple bits (as shown in Figure 3-5) instead of a pair of frequencies to represent a single bit. As in the case of BFSK or MSK, each frequency must be separated by 1/T Hz or 1/(2T) Hz. For example, an 8-ary FSK has eight different symbols, each represented by a different orthogonal frequency. Each frequency thus corresponds to a different 3-bit symbol. M-ary FSK takes up more bandwidth than BFSK running at the same bit rate (except for the special case of M = 2 where they are the same). However, if the bandwidth could be increased, a lower SNR would be required for a given bit rate, so
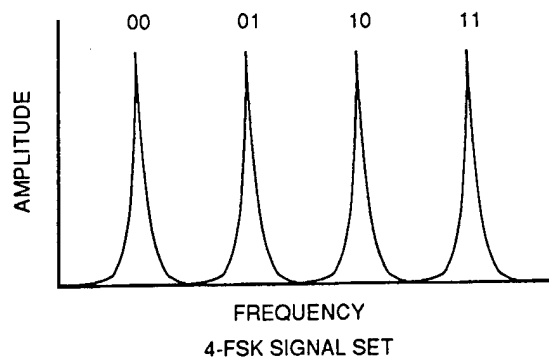
FIGURE 3-5 M-ARY FSK MODULATION

M-ary FSK/MSK modulations are particularly well suited for power-limited applications (Proakis, 1989). Like BFSK and MSK, this modulation has a constant envelope and can have continuous phase.

Biorthogonal M-ary FSK is created using an M/2 orthogonal symbol set and adding the negative of all the symbols to the set. In this case, the symbols correspond to a set of frequencies and the inverted set of the waveforms. The bandwidth required is half of that needed for the complementary orthogonal signal.

Differential binary phase shift keying (DBPSK) differs from the various FSK and MSK modulations in that it changes the phase of a single carrier instead of changing the frequency (as shown in Figure 3-6). These two symbols are antipodal instead of orthogonal as in BFSK. In differential signaling, the change in phase between two symbols represents the data. DBPSK is the current standard for MBC systems as defined in the Proposed Federal Standard 1055, where a change of phase of $\pi/2$ radians represents a *1* and a change of 0 radians represents a *0*. Because the phase of the received signal need be coherent with only the previous signal, no carrier recovery is needed.
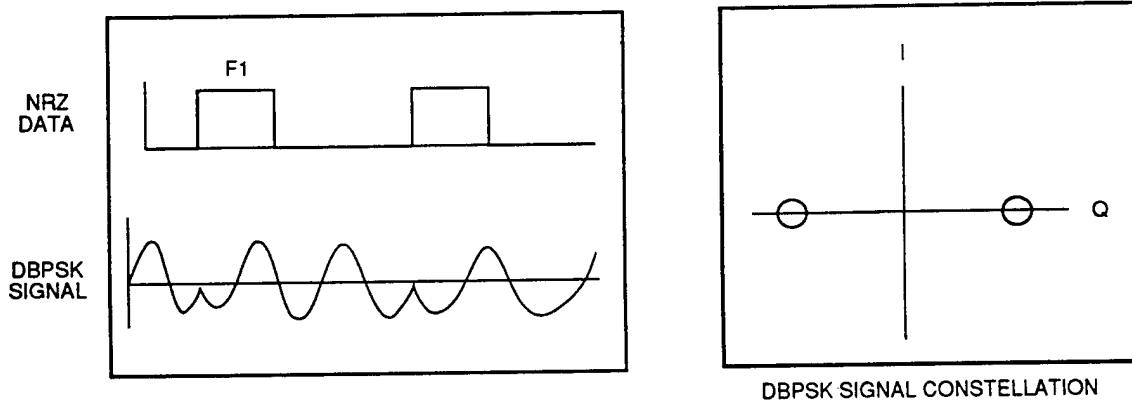
FIGURE 3-6 DBPSK MODULATION

14

Quadrature phase shift keying (QPSK) is a variation on BPSK with four phase states ($\pi/4$, $3\pi/4$, $5\pi/4$, and $7\pi/4$) instead of two (as shown in Figure 3-7), so each symbol represents two bits. This modulation is equivalent to using two coherently orthogonal signals and modulating alternating bits on each signal. Because the signals are coherently orthogonal, they do not interfere with each other. By sending two signals in the same bandwidth, QPSK achieves twice the bandwidth efficiency of DBPSK. QPSK can also be implemented as a differential modulation, which does not require carrier recovery.
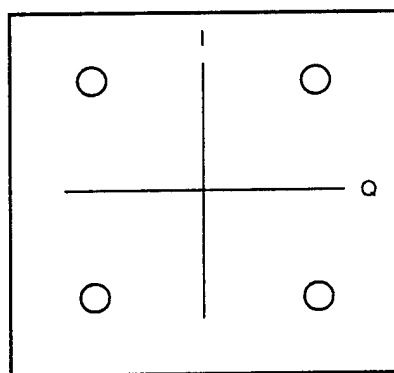
QPSK SIGNAL CONSTELLATION

781-9

FIGURE 3-7 QPSK MODULATION

M-ary PSK is a generalized implementation of PSK with a symbol set size of M (as shown in Figure 3-8), so QPSK is simply a special case with M = 4. Of course, SNR must be increased in proportion to M to maintain a given BER, but the larger symbol constellation improves the bandwidth efficiency.
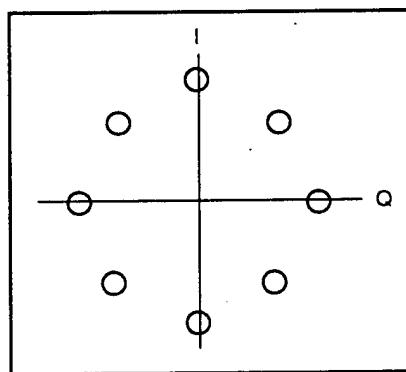
8-PSK SIGNAL CONSTELLATION

781-10R

FIGURE 3-8   M-ARY PSK MODULATION
FOR M = 8

15

Quadrature amplitude modulation (QAM) varies both the amplitude and phase of the signal to transmit the data (as shown in Figure 3-9). Carrier recovery is needed to generate a reference phase at the receiver for phase demodulation. A reference amplitude is also needed, which requires an automatic gain control (AGC) on the front end of the receiver before the demodulator. The AGC cancels out long-term amplitude variations in the channel, but lets the quickly changing amplitude modulation pass through. As with M-ary PSK, QAM can have various symbol set sizes and is very bandwidth efficient: typical cases are QAM-16, QAM-32, and QAM-64. QAM is very spectrally efficient, and it requires less of a power increase than M-ary PSK to maintain the same error rate performance. However, it is not clear that the necessary AGC could be designed to differentiate between variations in signal amplitude due to modulation and variations due to the channel itself, particularly for underdense trails. Thus, for reasons of performance, cost, and complexity, QAM is not recommended for the MBC system.
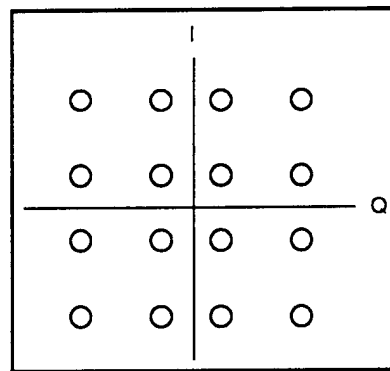
QAM SIGNAL CONSTELLATION

781-11R

FIGURE 3-9 QUADRATIVE AMPLITUDE
MODULATION FOR M = 16

Trellis-coded modulation (TCM) is not strictly a type of modulation, but is a combination of modulation and coding. The underlying modulation is typically M-ary PSK or QAM, and the code is a convolutional code (as shown in Figure 3-10). As will be discussed further in Section 3.1.3, the required SNR for a certain BER can be reduced by adding convolutional coding to a system, typically by adding redundant data bits to the data stream. The data rate must then be increased to compensate for the additional bits to maintain the same data rate as a system without coding. A 1/2-rate coded system requires a data rate twice that of an uncoded system. However, if the data rate is increased by changing the symbol rate, the bandwidth required also increases, which is undesirable for the band-limited MBC channel.

The advantage of TCM is that it accommodates redundant data bits by increasing the number of symbols in the signal constellation while maintaining the same symbol rate. An increased symbol set size compensates for the added redundant data, keeping the symbol rate constant for the same information bit rate (excluding coding bits). Thus, TCM adds coding while retaining the original bandwidth, so that its bandwidth efficiency depends on the underlying modulation and the degree of coding. The greater noise effects caused by the more closely spaced symbols are

16
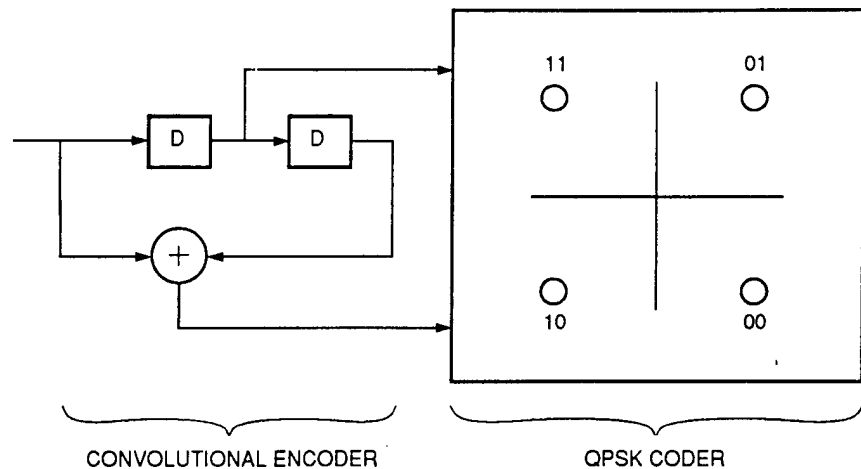
FIGURE 3-10   TCM WITH QPSK MODULATION

overcome by the coding gain from the convolutional code; for a band-limited channel like MBC, we can expect a coding gain of 3 to 6 dB when TCM is added to the system (Viterbi et al., 1989). For example, an uncoded system might use BPSK. The corresponding TCM system would use a combination of a 1/2-rate convolutional line coder, which adds a code bit to each information bit, and a QPSK line coder to send 2 bits as one symbol. Thus, the symbol rate of the system remains constant although the bit rate has doubled, and the coding gain is achieved without increasing the bandwidth.

3.1.2 Simulations and Evaluations

As shown previously in Figure 3-1, we used our empirical model of meteor trails combined with Matlab simulations of the modulations to evaluate performance under realistic MBC conditions. The results of the throughput simulations for the various modulations are shown in Figure 3-11. The results are given relative to the throughput for DBPSK, which is the current standard MBC modulation as described in Proposed Federal Standard 1055. These results are discussed below for each of the modulations in turn. Useful background for these discussions, especially with regard to bandwidth efficiency, can be found in Proakis (1989). Although the discussions involve theoretical considerations, the results shown in Figure 3-11 and our conclusions are based upon the results of our empirical model.

Differential binary phase shift keying (DBPSK) is the standard used here for comparison; its performance would be unity if shown explicitly in Figure 3-11.

Binary frequency shift keying (BFSK) shows the worst performance of any of the modulations evaluated here, primarily because of its poor spectral efficiency, which is slightly less than 1 b/s/Hz. The attraction of this modulation has always been the simplicity, reliability, and low cost of its associated hardware. However, current technology makes the cost difference between BFSK and BPSK marginal, making it unlikely that BFSK will be the preferred modulation for MBC applications. Also, BFSK is a special case of M-ary FSK with M=2, and for larger values of M

17
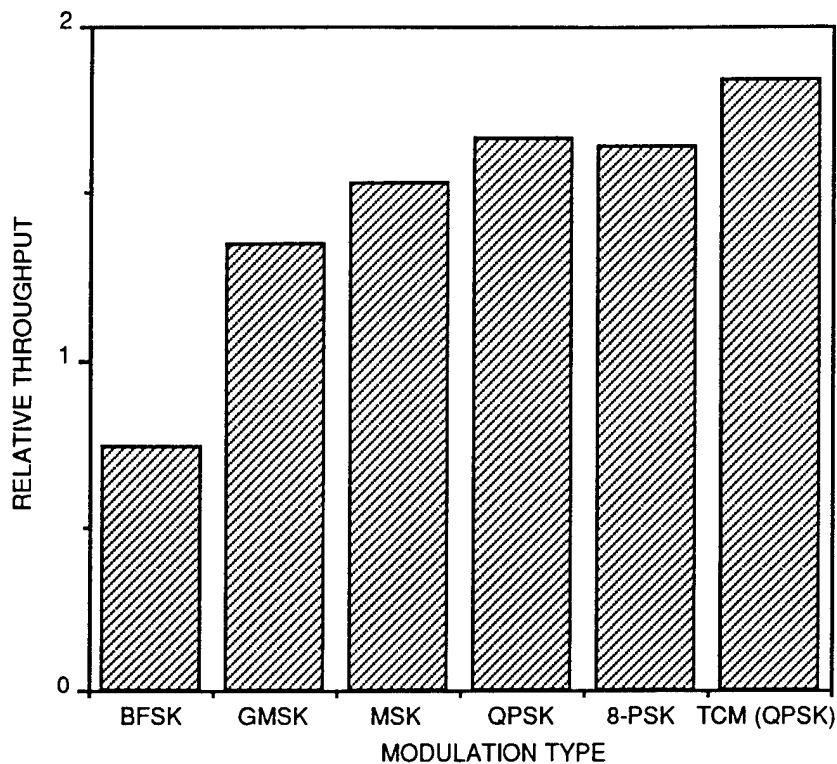
FIGURE 3-11 THROUGHPUT RELATIVE TO DBPSK

the spectral efficiency degrades and eventually approaches zero according to the expression $(2\log_2 M)/M$, so M-ary FSK should not be considered for a band-limited system.

Gaussian minimum shift keying (GMSK) can also be seen to perform well, although not quite as well as simple MSK because of the small loss of signal strength in passing through the filter. GMSK's greatest advantage is its resistance to interchannel interference, but as the geometry of MBC links generally does not permit different links to use the same trail, adjacent frequency channels typically do not interfere with each other anyway. For mobile MBC systems, however, multiple terminals might occasionally be located close enough together to be in the same footprint, making GMSK attractive for some mobile applications. GMSK systems will cost slightly more than MSK systems because of the filter, which also adds a small technical risk.

Minimum shift keying (MSK) can be seen to have a much better throughput than BFSK, primarily because its spectral efficiency is 2 b/s/Hz. When a coherent receiver is used for MSK and the signal is demodulated over two symbols, MSK should theoretically show about the same BER as BPSK. They should be equal because, although the two signaling symbols are orthogonal over one symbol period in the case of MSK, they are antipodal over two symbol periods for MSK and are always antipodal for BPSK.

Quadrature phase shift keying (QPSK) can be seen to have one of the best performances of the modulations tested. QPSK's use of two orthogonal pairs of antipodal symbols makes it more spectrally efficient than DBPSK, but with nearly the same symbol error rate. If QPSK is implemented with a coherent receiver, it will be somewhat more complex and costly than DBPSK,

18

but this disadvantage could be removed by adding differential coding to QPSK to eliminate the need for carrier recovery. In a similar theoretical study where only underdense trails were considered, QPSK was also chosen as one of the best modulations to use on an MBC channel (Morin, 1987).

M-ary PSK with M > 4 is a very spectrally efficient modulation; however, as M increases in a fixed bandwidth system like MBC, the signal decision region for each symbol becomes exponentially smaller. To keep the same error rate, the average power in the signal must increase as $(M/\pi)^2$, but in our simulation, we kept the same power level for all modulations. For this reason, it can be seen in Figure 3-11 the 8-PSK throughput is not quite as good as that of QPSK. Because 8-PSK systems also have a higher cost and complexity than QPSK, M-ary PSK should not be considered as the first choice for MBC systems.

Trellis-coded modulation (TCM) can be used in theory to add coding gain to any of the M-ary modulations, such as FSK, PSK, and QAM. However, some consideration must be given to how the symbol set is increased to add the redundant coding to the system. In the case of FSK, when the symbol set is enlarged, the bandwidth of the signal must be increased, which is not acceptable in our case. On the other hand, for PSK and QAM, the bandwidth remains the same, but, as discussed, QAM is probably not suitable for MBC applications. Thus, the results shown for TCM in Figure 3-11 (which are taken from Jacobsmeyer, 1992), are based on using QPSK as the underlying modulation. Because of the superior performance of this combination, as shown in Figure 3-11, we recommend it as the preferred advanced modulation. It uses the 1/2-rate K=7 convolutional code with polynomials G0=171 octal and G1=133 octal, which has become the *de facto* industry standard and is available on a number of commercial chips (Qualcomm, 1991; Edwards, 1990). Although special attention must be given to the associated delay caused by adding coding to the decoder, because it can affect the techniques used for carrier recovery and adaptive filtering, it should be possible to implement TCM for MBC applications with no significant performance loss.

3.1.3 Error Correction Coding

As with any communication channel, errors are generated in an MBC bit stream whenever noise is large enough relative to the received signal to change the output of the demodulator from its correct value. Because SNR changes over a range of perhaps 10 to 20 dB over the duration of all meteor trails before eventually decaying to the detection threshold at the end of the trail, errors are inherently part of the data received via every meteor trail. It is convenient to discuss the errors in different parts of a trail following the definitions introduced by Crane (1988) and illustrated in Figure 3-12. As this figure shows, the initial portion of the trail maintains a high SNR and low bit error rate. As the SNR decreases due to the trail decay, isolated random errors begin to appear. As the trail nears the end of its usefulness, bursts, or groups of errors occur more and more frequently until the SNR decreases to a point where useful communications cannot be continued. The period near the beginning of the trail when the SNR is so high that there are no errors is called the *error-free gap*. This period is included in what is called the *initial burst-free gap*, which is typically about 2.5 times as long as the error-free gap. Finally, the end-burst gap is defined in turn to include the burst-free gap, and it is typically about 4 times as long as the error-free gap.

UNDERDENSE TRAIL

LENGTH OF TRAIL

END-BURST GAP

INITIAL BURST-FREE GAP

INITIAL ERROR-
FREE GAP

BIT
ERRORS

809-6
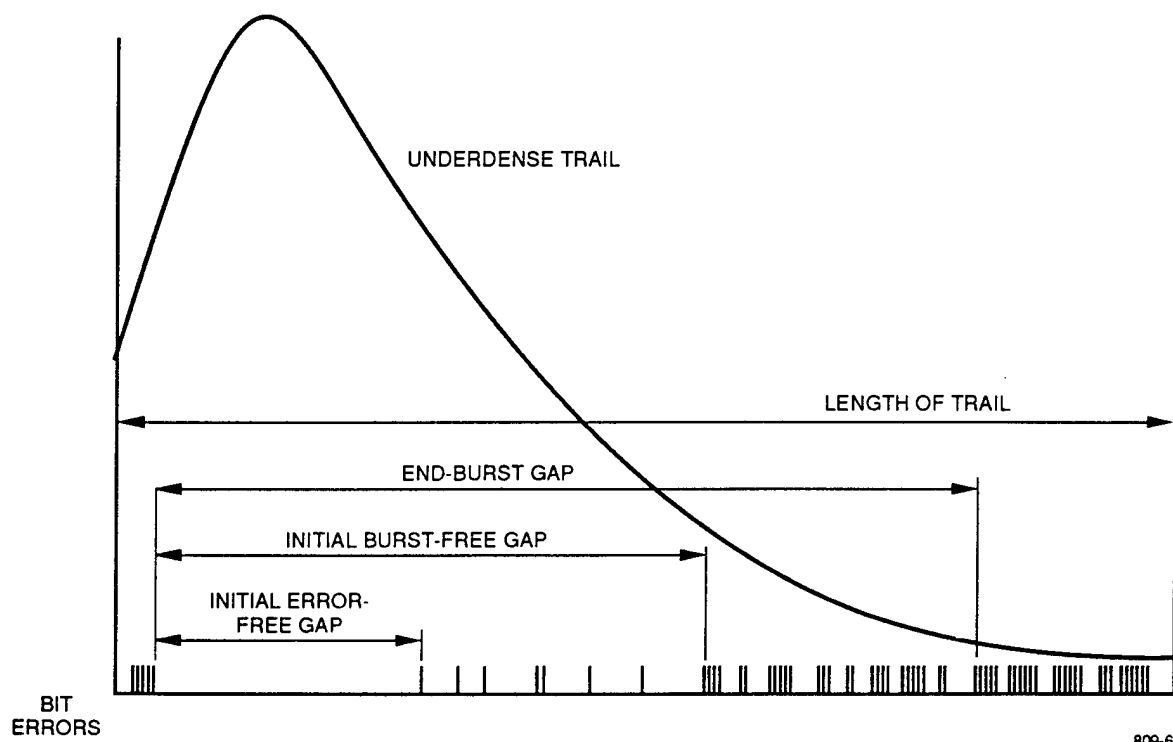
FIGURE 3-12 ERROR OCCURRENCES DURING A TYPICAL METEOR TRAIL

In some applications, it is essential that error-free data be received, and a variety of methods are available to achieve this goal. However, even aside from the matter of data integrity, error correction coding should be included in advanced MBC systems because it is another technology that can substantially increase system performance in terms of throughput. Although error correction coding is not strictly a modulation, it is discussed here with advanced modulations because modulations and coding are typically combined in a manner that makes them logically a single entity.

3.1.3.1 Methods of Error Control

Loop or Echo Checking. One of the simplest methods of error detection and correction is loop or echo checking—simply echoing the received data back to the transmitter from the receiver. If the echoed message differs from the transmitted message, the erroneous portion of the message is retransmitted and the process repeated. Obviously, this method is very limited. If the echoed message differs from the transmitted message, there is a 50% chance that the error occurred on the return path and that the original transmission of the message was accurate. Because the meteor burst channel has a tendency to decay over time, the return path will most often have a higher error probability than the forward path. Therefore, false-error events at the transmitter can lead to an unnecessary increase in repeated data and a significant reduction of throughput. For this reason, this simple method of error correction is not a good choice for meteor burst systems.

Automated Repeat Query (ARQ). ARQ is a more sophisticated method of error detection and correction. This procedure involves attaching redundant check bits to messages for error detection.

20

If an error is detected, a repeat message request (called a *negative acknowledgment*, or NACK) is returned to the transmitter. In a half-duplex system, the transmitter must send the message and then wait for a positive or negative acknowledgment (ACK/NACK) from the receiver to continue. Clearly, this waiting reduces throughput.

One ARQ scheme uses a negative acknowledgment combined with a request for repeat of the last n data blocks. In this case, the transmitter does not need to wait for an acknowledgment to continue. Individual data blocks do not need to be labeled, which cuts down on the overhead, and the repeat request algorithm is simpler than it is for the selective repeat request ARQ discussed below. However, this method limits transmission range because the round-trip delay of the repeat request must be less than the time required to transmit n data blocks to ensure that the erroneous block is indeed resent. Also, this method retransmits more data than are necessary to correct the one erroneous block. Popular values for n are 4 and 6 (Berlekamp et al., 1977).

The selective repeat ARQ scheme uses a negative acknowledgment combined with a request for repeat of the specific erroneous block only. This method increases the efficiency of the retransmission as only the erroneous block is repeated. However, the need to label the blocks increases the overhead. The range between stations is limited only by the block counter and system memory. Block length is an important consideration as longer blocks are more likely to contain errors and require more time for retransmission. However, a shorter block length will require more block overhead, more blocks to transmit the same amount of information, and a higher capacity block counter.

Overall, ARQ alone does not appear to lend itself well to meteor burst communications. Because of the relatively long wait time between trails (which can be up to a few minutes, depending on power-aperture product and other system parameters) a long round-trip delay can be expected when messages are not completed with a single trail. Because of the short available transmission time of the trails, block length will be limited. Again, shorter block lengths mean more overhead. After the initial error-free gap of the trail, random and burst errors can be expected to increase and communications will break down due to the increase in requests for repeats. Therefore, the part of the trail able to support error-free transmission using ARQ will be limited to only that portion of the trail with a very small bit-error probability. These limitations have been confirmed on an experimental high-latitude meteor burst channel (Brayer and Natarajan, 1988). However, they also showed that the addition of forward error correction coding to ARQ extends the useful part of the meteor trail and significantly improves overall performance.

Forward Error Correction (FEC). FEC is accomplished by adding specially coded bits to transmitted messages for the purpose of not only detecting errors, but also correcting those errors without the need for retransmission. There are two methods of adding the needed redundancy into the transmitted signal. The first is to add error detection and correction bits to the information bit stream, which is the method used in block codes and convolutional codes, as discussed below. Because of these additional redundant bits, the overall bit rate must be increased in order to maintain the same information bit rate. This increase in bit rate in turn increases the bandwidth and allows more noise into the receiver. The second method adds redundancy by increasing the alphabet size or symbol set size, which is the method used in trellis-coded modulation, as has been discussed. This method is usually preferred on band-limited channels (such as the meteor burst channel) because no increase in bit rate is required. The bit error rate will increase in both cases: the increase is due to the increased noise in the first case and the decreased detection efficiency in the second case.

3.1.3.2 Coders and Decoders

There are two fundamentally different types of decoders: hard decoders and soft decoders. In a hard decoder, the received signal is converted into digital information (symbols) by making decisions based on threshold levels (hard decisions). The detected symbols are then passed on to the decoder where the stream is corrected by inverting the encoding process. In the soft decoder, decisions are made on the received signal by assigning confidence values to the symbol detection (soft decisions). These confidence values are based on how far the detected signal is from the decision threshold. The confidence information is then used in the decoding and correction process, allowing for a better decision. Soft decoding is closely tied to the demodulation process and can provide better performance than hard decoding, but the improvement comes at the expense of increased complexity. Theoretically, soft-decision decoding has a 2-dB coding gain over hard-decision decoding (Keiser, 1989), but Mui (1991) has reported that soft Viterbi decoding provided an approximate 5 dB gain over hard decoding in a simulation of MBC performance. Because of complexity, block decoders use hard decoding exclusively, but convolutional decoders can use either hard or soft decoding. These codes and decoders are discussed below.

Block Codes. In an (n,k) block code, k information bits are coded into an n-bit message stream. Therefore, (n-k) redundant bits are added to the source information for purposes of error detection and correction. Block codes are said to be memoryless; that is, the coded block depends only on the source bits, and successive bits in the coded block are independent of one another. Block codes require a synchronization scheme so that the decoder can identify the start of each block, which adds to the overhead and requires the types of tradeoffs related to block size that were discussed above. Many different block codes have been developed over the history of FEC. A subset and their MBC applications are discussed below.

Hamming codes consist of a family of (n,k) block codes where $n = 2^m-1$ and $k = n-m$ for any positive integer m. However, these codes can detect only two errors per block and correct only one error per block. Because of this limited error detection and correction capability, block lengths must be relatively small, decreasing the coding rate, the fraction of bits containing the source information, or (k/n). Also, with Hamming codes, burst errors cannot be corrected at all.

The family of cyclic block codes comprises the most practical block codes with the most efficient encoders and decoders, usually made up of feedback shift registers and modulo-2 adders. An (n,k) linear block code is cyclic if any cyclic shift of a codeword produces another codeword. The Bose-Chaudhuri-Hocquenghem (BCH) codes consist of blocks of length $n = 2^m-1$, for all positive integers m greater than two. These codes can correct any pattern of e or fewer errors using no more than (m×e) redundant bits. These codes are especially useful for detecting and correcting randomly occurring multiple errors. The Reed-Solomon (RS) codes, which are actually a subset of BCH codes, consist of blocks of length $n = 2^m-1$ symbols (where each symbol is represented as m bits). These codes can correct any pattern of e or fewer errors where e = (n-k)/2. These codes are well suited to correcting short bursts of errors as well as isolated random errors.

Adaptive-Rate Block Codes. For MBC applications, it would seem that a clear advantage could be gained by using an adaptive-rate block-coding scheme in which the blocks near the beginning of the trail use a higher coding rate than those near the end. This method should be able to provide a better throughput at the expense of the more complex encoders/decoders required to

adapt themselves to the varying code rates. However, Frederick et al. (1991) compared three adaptive rate block coding methods for BCH and RS codes on a simulated MBC channel. These were the channel-capacity-rate-adapting (CCRA) method, the block-error-rate-adapting (BERA) method, and the method of Pursley and Sandberg (1989). The performance measure for their simulation was the probability of successful delivery of a fixed-size packet using a single meteor trail. The CCRA and BERA adaptive coding strategies selected the number of information bits (or symbols) per block based on the SNR. The CCRA method was based on keeping the information transmission proportional to the theoretical channel capacity, while the BERA method was based on keeping the block error probability below a certain threshold. Both methods required the transmitter to know the SNR of the link for each block in order to make decisions on the optimum rate. On the other hand, the Pursley-Sandberg method was based on the initial SNR and an assumed channel model. The Pursley-Sandberg method was found to be better than the other two methods, but not by very much. In fact, the conclusion of their study was that a convolutional coder (discussed below) with soft Viterbi decoding out-performs the three adaptive-rate-block-coding methods.

Convolutional Codes. Convolutional codes are so named because the redundant bits are generated by modulo-two convolutions. The block diagram for a 1/2-rate, K=3 convolutional code is shown in Figure 3-13. For a 1/2-rate code, a code bit is added to each information bit, and K is the number of shifts over which a single bit will influence the encoder's output. These codes are said to be a finite memory system because the successive coded bits are related to each other via the modulo-two addition. The relationships are exploited in decoding, where the history of the bit stream is used in the decision process. One disadvantage of this decoding process is that mistakes
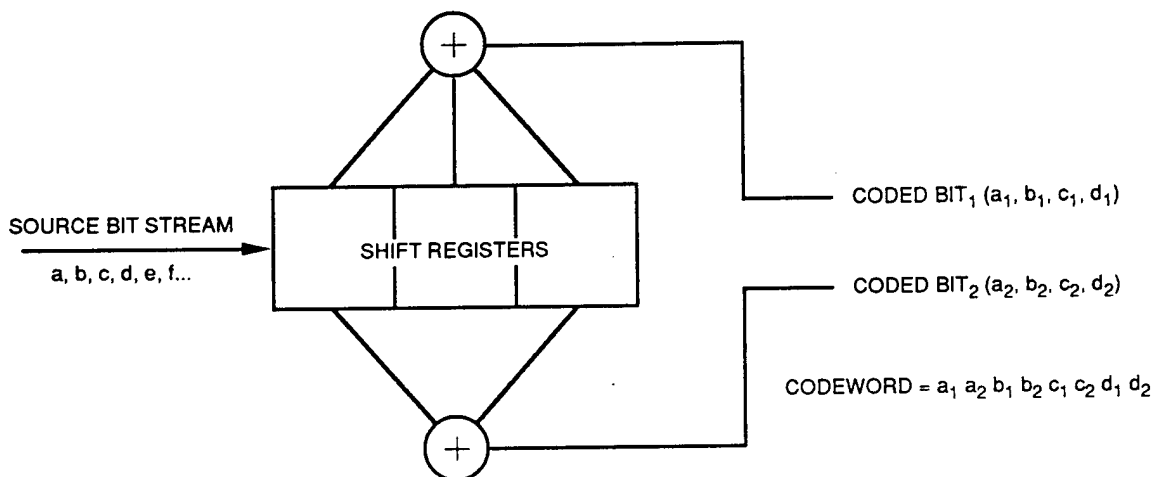
FIGURE 3-13   BLOCK DIAGRAM FOR A CONVOLUTIONAL CODE
(Rate = 1/2, K = 3)

can propagate and the decoder can take a while to recover from a burst of corrupted data. Also, because the decoder has to perform large numbers of operations per decoded bit (the number depends on the constraint length, K), the transmission speed must be slow enough to allow

23

decoding. Typical data rates for MBC systems range from only about 2 to 128 kb/s, which is slow enough that modern DSP capabilities are easily adequate for the popular and powerful K=7 convolutional code (Berlekamp et al., 1987).

Synchronization is not a concern with convolutional codes as it is with block codes, and, in general, convolutional codes are simpler to implement than block codes and lend themselves to practical soft decoding schemes (such as soft Viterbi decoding) available on many commercial decoding chips (Edwards, 1990). The performance of convolutional codes matches and often exceeds that of good block codes, as was noted by Frederick et al. (1991). Also, Mui (1991) has shown that the use of coding for MBC can reduce the required SNR by many decibels, and he gives an example of a 6-dB improvement for a 1/2-rate, K=7, soft Viterbi, convolutional code with interleaving compared with an uncoded system.

In the paper mentioned above, Frederick et al. (1991) have compared the performance of six coding methods on a simulated underdense meteor-burst channel: two were fixed-rate BCH and RS codes; three were adaptive block coding schemes; and one was a simple, 1/2-rate, K=7, convolutional code with hard-decision Viterbi decoding. For one set of MBC channel parameters, they found that this simple convolutional code outperformed the fixed-rate BCH code and adaptive BCH coding schemes by approximately 5 to 6 dB and the fixed-rate RS code and adaptive RS coding schemes by approximately 6 to 7 dB. For a second set of channel parameters, they found that the convolutional code outperformed the fixed and adaptive rate codes by approximately 1 to 4 dB, except during the initial high-SNR portion of the trail where the adaptive-rate block codes performed better by approximately 1 dB. They suggested that a higher rate convolutional code might have performed better even in these cases. Frederick et al. also mentioned that soft-decision decoding for the convolutional code would be expected to improve on this performance by at least 2 dB. Finally, they concluded that the ease of implementation of convolutional codes and the complexity of adaptive-rate block codes, along with the performance results of their simulations, make convolutional codes (presumably with soft Viterbi decoding) a good choice for MBC systems.

Trellis-coded Modulation. TCM, as mentioned previously, is a convolutional code in which the error control redundancy is added via an enlarged alphabet size or symbol set size, and it is preferred for MBC applications because the symbol rate and, therefore, the bandwidth, is not increased. However, because the symbols are more closely spaced, noise immunity is reduced, and the coding gain must compensate for this consequence. The substantial advantage of including TCM in an MBC system was shown previously in Figure 3-11.

Interleaving. As was shown in Figure 3-12, bursts of errors will always occur in at least a few places in the uncorrected data stream received via a meteor trail. For error detection and correction to work on burst errors, either the information bits or the redundant coding bits must be outside the burst of corrupted data. The best method of dealing with this problem is known as interleaving. Figure 3-14 shows two simple interleaving techniques. In the example of delay interleaving, another level of redundancy is added to the transmitted data as the bit stream is delayed by three bits and then interleaved with the original stream. Through error detection on each bit, the correct bit of the pair is used, so that a burst error of three bits or fewer can be overcome.
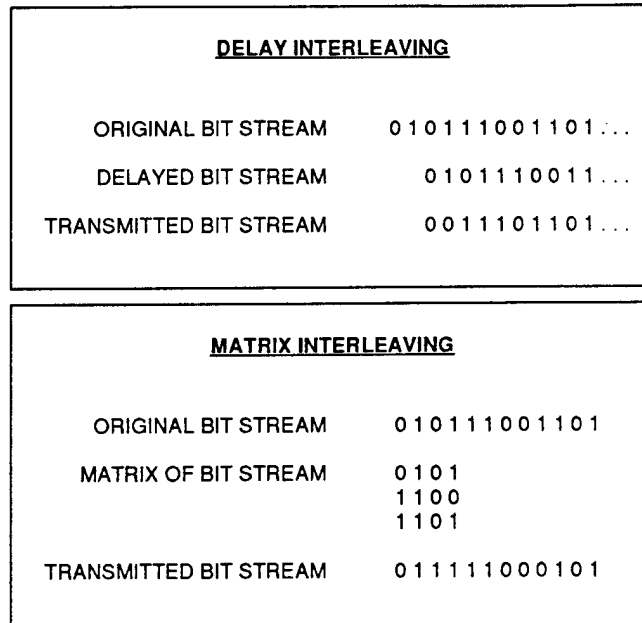
```
                    ┌─────────────────────────────────────────┐
                    │          DELAY INTERLEAVING             │
                    │                                         │
                    │                                         │
                    │  ORIGINAL BIT STREAM      0 1 0 1 1 1 0 0 1 1 0 1 . . . │
                    │                                         │
                    │  DELAYED BIT STREAM         0 1 0 1 1 1 0 0 1 1 . . .   │
                    │                                         │
                    │  TRANSMITTED BIT STREAM       0 0 1 1 1 0 1 1 0 1 . . . │
                    └─────────────────────────────────────────┘

                    ┌─────────────────────────────────────────┐
                    │         MATRIX INTERLEAVING             │
                    │                                         │
                    │                                         │
                    │  ORIGINAL BIT STREAM      0 1 0 1 1 1 0 0 1 1 0 1       │
                    │                                         │
                    │  MATRIX OF BIT STREAM     0 1 0 1                       │
                    │                           1 1 0 0                       │
                    │                           1 1 0 1                       │
                    │                                         │
                    │  TRANSMITTED BIT STREAM   0 1 1 1 1 1 0 0 0 1 0 1       │
                    └─────────────────────────────────────────┘
                                                    809-9
```

FIGURE 3-14   ILLUSTRATION OF TWO SIMPLE
               INTERLEAVING TECHNIQUES

In the example of matrix interleaving shown in Figure 3-14, the original bit stream is input into the rows of an (n×m) matrix. The m columns of this matrix are then transmitted sequentially. In this way, the original bit stream is divided into n blocks of m bits each, and no extra redundancy is added. The first column of the matrix then holds the first bit of each of the n blocks, the second column holds the second bit of each block, and so on. Therefore, if a burst error occurs, it is more likely that just one bit of each block will be corrupted rather than several bits of one block. The usual error-correction schemes can then be used for correction of each block. Interleaving does add a delay to the system in that the interleaving of the received bit stream must be removed before decoding can take place. However, MBC data rates are so low that this delay is not a problem. As pointed out by Crane (1988), an interleaver will generally extend the usable bit stream up to the length up to the end burst gap, but attempts to extend beyond this gap probably are not worthwhile.

One example of an evaluation of interleaving for MBC applications has been given by Al-Jabri (1990). He used a matrix method similar to the one described above, except that all odd columns were transmitted in a top to bottom order while all even columns were transmitted bottom to top. He found that this simple interleaving scheme provided virtually the same performance improvement as a more complex variable-rate coding scheme. Another example has been given by Mui (1991) who stated that for convolutional encoding and Viterbi decoding, interleaving has been found to be effective in combating Rician fading and is expected to be effective in combating the exponential fading associated with the underdense meteor burst trail. He used a 20×20 block interleaver, a 1/2-rate, K=7 convolutional code, and Viterbi decoding, but he did not show an explicit comparison of interleaved and noninterleaved performance.

25

Hybrid ARQ-FEC. As discussed, ARQ can provide constant data quality, but the throughput collapses as errors increase. Also, FEC can ensure a constant throughput, but the data quality depends on the channel error characteristics. Thus, a hybrid ARQ-FEC has obvious attractions. One hybrid ARQ-FEC scheme attaches one set of redundant bits for FEC and another for ARQ. Errors in the message are first detected and corrected using the FEC bits. The correction is then checked using the additional ARQ check bits. If an error is detected, a request for repeat is triggered. The efficacy of this approach depends highly on the FEC used, as the ARQ is triggered by the inability of the FEC to correct the data. One disadvantage is that the redundant FEC bits are attached to the data even when channel errors are not present.

In another hybrid ARQ-FEC scheme, messages are sent with detection check bits only. If an error occurs, an ARQ is triggered. However, the transmitter does not repeat the data; instead, it sends the FEC redundant code bits with additional error-detection check bits attached. If these bits are received intact, the original message is corrected, but if they also contain errors, an attempt is made at correction. If this is unsuccessful, an ARQ is sent again either for the original message or for the FEC redundant code bits. Obviously, this method can use only block code FEC, because the code bits need to be separated from the information bits. The advantage of this method is that the redundancy for the FEC is not transmitted until it is needed, but the method does not appear to be well suited for the meteor burst channel. Because of the short lifetime of meteor trails, ARQs should be kept to a minimum, but this method triggers an ARQ every time an error is detected rather than every time an error cannot be corrected. Thus, ARQ uses a larger percentage of available channel time, especially during the latter parts of the trail. Also, the requirement that it use only FEC block codes could be a disadvantage, since convolutional codes could be better suited to MBC applications than block codes.

Brayer and Natarajan (1988) tested a hybrid ARQ-FEC method of the first type (above) over a high-latitude MBC path. They found that a small amount of coding improved performance significantly, but more so for long messages (400 bits) than short messages (40 bits). They also showed that it was possible to have too much coding; performance began to degrade as the overhead involved with the addition redundancy caused more messages to extend into the trail's end-burst-error region. Therefore, adding some FEC coding to their ARQ scheme extended the usefulness of their meteor trails beyond the error-free region and into the region of isolated random errors, which, of course, improved the system performance.

3.1.3.3 ARQ-FEC Strategy for Advanced MBC Systems

The data quality requirement for advanced MBC systems can be expected to depend strongly on the specific application of each particular system. Thus, the standards that will guide the development of these systems must be structured to permit selection of error-correction techniques that provide the desired quality without unduly compromising either the cost of the system or the quality of its performance. A hybrid ARQ-FEC system seems best suited to this situation because throughput and error rate can be traded off to achieve any desired balance. As we have shown, systems that use ARQ alone are not well suited for the meteor burst channel, but a significant improvement in performance can be achieved with only small amounts of additional coding in a hybrid ARQ-FEC system. The performance of any hybrid ARQ-FEC system will depend on the quality of the FEC, as it is the failure of the FEC that controls the need for data repetition.

If the data quality requirement is set so that the system can tolerate small error rates, or if the throughput of the system is the main system design driver, then a good FEC, capable of meeting the error rate requirements, is clearly indicated. Much of the literature deals with block codes, but very simple convolutional codes exist that can outperform both fixed-rate and adaptive-rate block codes. In particular, the 1/2-rate, K=7 convolutional code has good coding gain, especially in conjunction with soft Viterbi decoding, a capability currently available on commercial chips. Other codes, such as 3/4 and 7/8, may have some advantages and should also be evaluated for possible application in advanced MBC systems. A matrix method of interleaving should also be used because it will improve performance in the presence of burst errors without the need for additional coding bits. Based on the increased performance of adaptive-rate block codes over fixed-rate block codes, it is also expected that performance improvement could be achieved with adaptive-rate convolutional codes. Additional study in the areas of convolutional codes, adaptive-rate convolutional codes, and interleaving with convolutional codes appears warranted for the purpose of developing advanced standards.

Because of the band-limited nature of the meteor burst channel, trellis-coded modulation and adaptive trellis-coded modulation can provide higher performance improvement than other convolutional codes. As will be discussed in Section 3.2, adaptive TCM shows very good performance for MBC applications, and it is recommended for the baseline version of an advanced MBC system.

3.1.4 Recommendations

As a summary of the results presented in Section 3.1, we recommend that the modulation for the advanced MBC system be TCM using QPSK with a convolutional code with rate 1/2, K=7, and polynomials G0=171 octal and G1=133 octal. The system should also include an ARQ-FEC protocol, including matrix interleaving, which requires retransmission only when errors cannot be corrected. This recommendation is elaborated somewhat in Section 3.2.4 after consideration of adaptive data rates.

3.2 Adaptive Data Rates

Because the rate at which data can be communicated through any given channel is proportional to the SNR, an adaptive data rate (ADR) capability can provide increased throughput in advanced MBC systems by adapting the bit rate in real time to changes in SNR that occur from trail to trail and within each trail. Increased throughput results not only from increasing the data rate to take advantage of periods of high SNR but also from reducing the data rate to exploit weak signals that otherwise would have been missed. A system with a fixed bit rate and BER will not be able to utilize trails for which the SNR is always below the SNR required for that particular combination of bit rate and BER. However, if the data rate can be reduced, the threshold SNR will be lowered, and the waiting time between adequate trails will be shorter because there are so many more meteors that make the smaller trails.

The current Federal Standard 1055 defines a fixed-rate MBC system that does not take advantage of varying SNR. The challenge for ADR techniques is to adjust the data rate to keep the system near maximum performance, which means as high a data rate as the SNR allows while also maintaining a constant BER, or constant E_b/N_0. A second challenge is to minimize the ADR

overhead to have a net increase in throughput. The data rate can be changed by varying either the actual symbol rate or the symbol set size.

In this section, we evaluate ADR techniques in much the same way as we did advanced modulations in Section 3.1. We rely on the published reports of other work as well as on Matlab simulations of the various techniques convolved with the SRI channel model. As the underlying modulation for these ADR techniques, we use M-ary PSK. For most cases, we use DBPSK, the current MBC standard for modulation. For the techniques that require higher-order modulations, we use QPSK, 8-PSK, 16-PSK, etc., as appropriate. We also take note of experimental results reported for ADR systems tested in the field, and we take account of cost and complexity as well as increases in performance in choosing a recommended system.

For these evaluations, we limit the channel bandwidth to 16 kHz as specified by the National Telecommunications and Information Administration (Cohen et al., 1989). This limitation gives a big advantage to bandwidth-efficient ADR techniques.

3.2.1 Basic Requirements

There are three basic requirements for implementing any ADR system: accurate and timely determination of the SNR; communication of the bit rate information from the transmitter to the receiver; and a variable bandwidth filter (Chang et al., 1992). In the following discussions, we assume that a base station broadcasts an ADR signal to a remote site. The link may be full duplex, but we focus on the process of establishing the ADR link from the base station transmitter to the remote receiver.

SNR Determination. One method of determining the SNR is to assume reciprocity, which means to assume that the propagation effects are the same in both directions, so the received signal strength at the base station can be used to estimate the SNR at the remote site. A typical link might consist of a base station transmitting an ADR signal to a remote station and the remote station transmitting a constant probe signal back to the base station. This probe can be the second part of a full duplex link or a simple CW signal. The base station measures the SNR of the received probe and uses it to estimate the SNR at the remote site. The data rate is then changed according to the remote SNR estimate.

The problem with assuming reciprocity is that the signal and noise conditions are generally different at the two sites. The local noise and interference environment can be expected to be unique to each place and time. If separate antennas are used for transmitting and receiving, antenna aiming differences can also result in discrepancies in the signals received at the different locations. The sensitivity of the two receivers or the output power of the transmitters may also be different. Typically these problems can be overcome by careful calibration of the remote and master systems, but the problems must be recognized and minimized if reciprocity is to be assumed.

Another method of SNR determination is actually to measure it at the remote receiver and then to transmit the result back to the base station over the reverse link. This method is somewhat more complicated than simply using a probe and assuming reciprocity, but the increase in complexity is not sufficient to outweigh its advantages.

28

Communication of Data Rate. The remote station needs to know the data rate so it can adjust its demodulator's timing recovery circuits and also change the variable bandwidth filters, if needed. The most straightforward method of providing this information would be to use a second dedicated channel to communicate it directly, but this approach will not be attractive if it requires added spectrum and separate hardware for the dedicated channel. However, Braun and Meyerowitz (1991) describe a method of this type that does not require additional spectrum. Their main channel uses DBPSK modulation, and their auxiliary channel consists of an amplitude modulation of the envelope of the DBPSK signal which indicates the bit rate. A filter at the receiving station then extracts the timing information from the main channel. Another method is to include the bit rate information for the next packet as a packet in the data stream itself. This method has the advantage that it does not require additional demodulation hardware at the receiving station, but the data rate will be slightly lowered by the increase in packet overhead.

Chang and Schilling (1992) have proposed another method which avoids these difficulties by having the receiver automatically identify the incoming bit rate by examining each packet as it arrives. The receiver contains three separate demodulators operating at three stepped symbol rates. One operates at the symbol rate of the previous packet, one operates a step below that rate, and the last a step higher. To determine which demodulator is operating at the correct rate, the receiver sums the demodulated bits over a packet. The demodulators that are running at the wrong rates will have their bits partially canceled, so the demodulator with the highest sum is operating at the correct rate. This system is part of the feedback-adaptive variable-rate (FAVR) system and is shown in Figure 3-15.
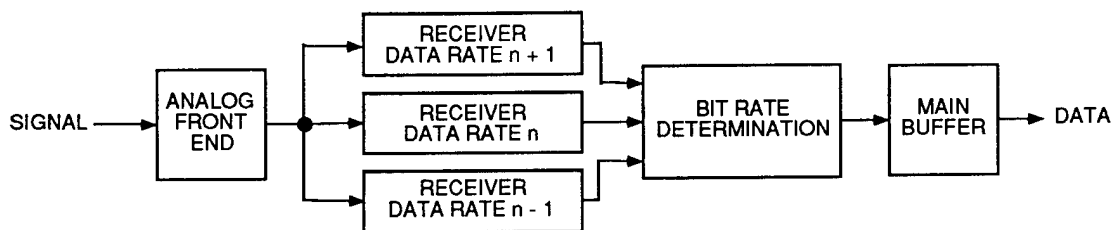
809-13

FIGURE 3-15   FAVR SYSTEM FOR AUTOMATIC BIT RATE DETERMINATION
(adapted from Chang and Schilling)

Adaptive Filtering. Some adaptive data rate techniques require adaptive filtering at the receiver and transmitter for maximum performance. For MBC applications, only subband filtering within the 16-kHz operating band can be used. One such technique changes the bandwidth of the transmitted signal as the bit rate changes, as illustrated in Figure 3-16. If the filter on the receiver is not adaptive but is set to accommodate the largest bandwidth of the signal, noise outside the bandwidth of the smaller signals will create a lower-than-necessary SNR. With an adaptive filter, when the bandwidth of the signal decreases, the bandwidth of the receiver will also collapse, thus allowing less out-of-band noise into the receiver and increasing the SNR because the signal power will remain constant while the noise power will be reduced. Fully adaptive filters can be fairly complex, but it is relatively simple for the bandwidth of the signal to follow the discrete steps of the different available symbol rates. For this simpler problem, various preset filters can be switched in

and out of the system, perhaps using different taps on a digital finite impulse response (FIR) filter. However, not all ADR techniques require adaptive filtering.
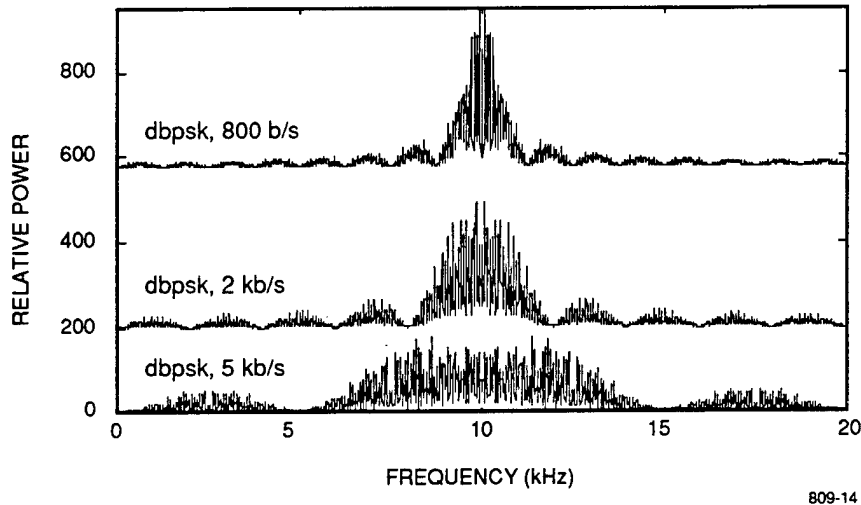
FIGURE 3-16 SYMBOL RATE BANDWIDTH REQUIRED FOR
DIFFERENT BIT RATES

All adaptive techniques entail a practical decision as to what discrete data rates are allowed. In an ideal system, the changes would be made continuously instead of in steps, but implementing such a system would be impossible. The lowest rate is often set at 2 kb/s, and the upper rate is, of course, set by the allocated operating bandwidth. For MBC systems, a 16-kHz bandwidth permits a maximum rate of 16 ks/s. DBPSK modulation uses one bit per symbol, and M-ary PSK uses $\log_2 M$ bits per symbol, so their respective bit rates can be as high as 16 kb/s and 4×16 = 64 kb/s for M = 16. The step sizes between rates are usually factors of two, but Chang and Schilling (1992) have suggested alternative step sizes of 4/3 and 3/2, which may be somewhat more difficult to implement but which results in an increased number of bits being sent in a given trail.

A decision must also be made as to when the bit rate can be changed, whether on bit boundaries (the rate can change between any bits in the data stream) or on packet or message boundaries.

3.2.2 Description of ADR Techniques

Fixed Rate. The current MBC Federal Standard specifies a system in which the data rate must be fixed either at 4 kb/s or 8 kb/s (Cohen et al., 1989). Once the rate has been set, it cannot be changed during normal operations. This system does not speed up to take advantage of trails with high SNR or slow down to compensate for lower-SNR trails. During periods of high SNR, the signal is transmitted with a higher BER than is typically required. The only advantage of this type of system is its simplicity and associated low cost.

30

Optimal Fixed Rate. Abel (1986) has proposed two ADR techniques. One fixes the data rate for each meteor trail at what is assumed to be an optimum value based on a trail model and an SNR measurement for the trail. The other varies the data rate during the trail as a function of the instantaneous SNR. The first method is referred to here as the *optimal fixed-rate* method. To set the optimal symbol rate for a particular trail, the transmitter must measure or estimate the peak SNR and its rate of decay. The benefits of this method are limited by the validity of the model used to predict the shape of the trail and by the random nature of the meteor burst trails. The model usually assumes that the trails are underdense and will show the typical exponential decay of SNR. Obviously, it will not work well for an overdense trail, and the trail may be underutilized because of the delay in estimating the peak SNR and decay rate. For example, if the system monitors the differential SNR, the peak will be discovered only after it has passed, and some of the best part of the trail will not be used. Figures 3-17 and 3-18 show the operation of an optimal fixed-rate system for two sample meteor trails with vastly different SNR and time scales, thus illustrating the increase in data rate for a larger peak SNR and a slower rate of decay. The maximum symbol rate is, of course, limited by the allocated bandwidth, and the minimum rate is typically set by practical considerations and by the desire to minimize the waiting time between trails. A typical minimum symbol rate is 2 ks/s.

Adaptive Symbol Rate (ASR). Although the optimal fixed-rate technique takes some account of SNR variations from trail to trail, the ASR technique also takes account of the SNR variations during each trail. In an ASR system, the symbol rate is varied in proportion to the SNR measured at the remote station receiver in a manner that keeps the BER (or E_b/N_o) constant. This system takes full advantage of periods when the SNR is high and faster symbol rates can be used. The rate is set according to the following formula given by Jacobsmeyer (1992):

$$
\begin{aligned}
R(t) &= P_r(t,q)/N_o(E_b/N_o) &&\text{for } R \geq R_{max} \\
&= R_{max} &&\text{for } R > R_{max}
\end{aligned}
$$

where

R_{max} = the maximum symbol rate allowed
$P_r(t,q)$ = the received power as a function of time and electron line density
N_o = the noise power at the receiver
E_b/N_o = the required SNR for a particular BER.

This system also allows for a decrease in symbol rate so that trails with low SNR can still be used efficiently by the system. An ideal ASR system with no limitations on the possible values of the symbol rate is the optimal ADR system for both maximum throughput and minimum waiting time. Figure 3-19 shows an example of ASR performance.

However, we must examine the performance of ASR techniques with the important limitation of a fixed maximum of 16-kHz necessary bandwidth and a 20-kHz channel spacing. This bandwidth limitation restricts the maximum symbol rate of the system (R_{max}) to 16 ks/s. There will be periods during a trail when the SNR warrants a higher symbol rate then Rmax, but during these times the trail will be underused because of the restriction on signal bandwidth. As stated earlier, as a practical matter, the symbol rates of an ASR system cannot be adjusted continually but must be defined in discrete steps. ASR also requires adaptive filtering on both the transmitter and receiver to match the varying bandwidth of the transmitted signal and to remove out-of-band noise

31
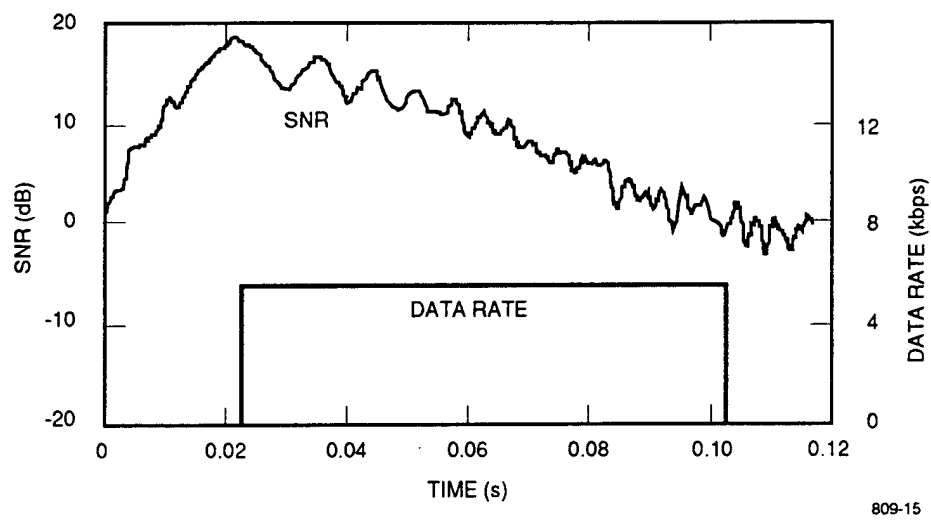
FIGURE 3-17   EXAMPLE OF AN OPTIMAL FIXED RATE FOR A SHORT TRAIL
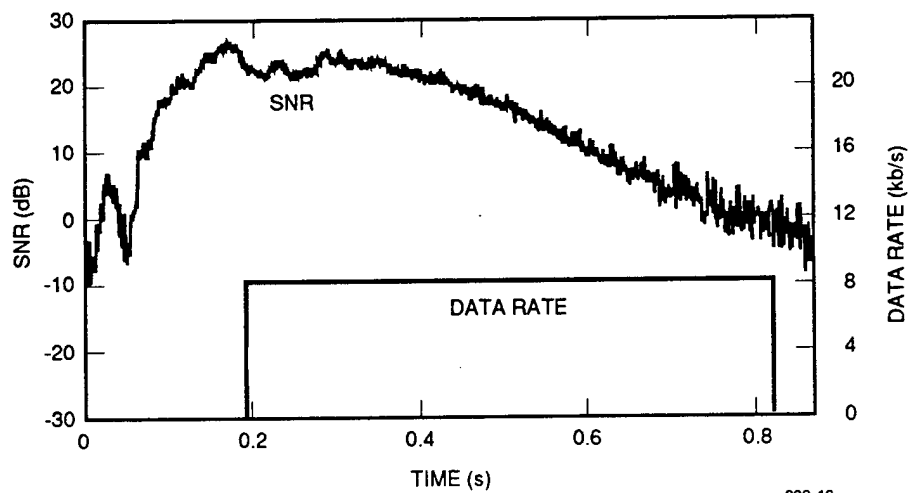
FIGURE 3-18   EXAMPLE OF AN OPTIMAL FIXED RATE FOR A LONG TRAIL

when rates less than R_{max} are used. These requirements distance ASR somewhat from the ideal ADR system.
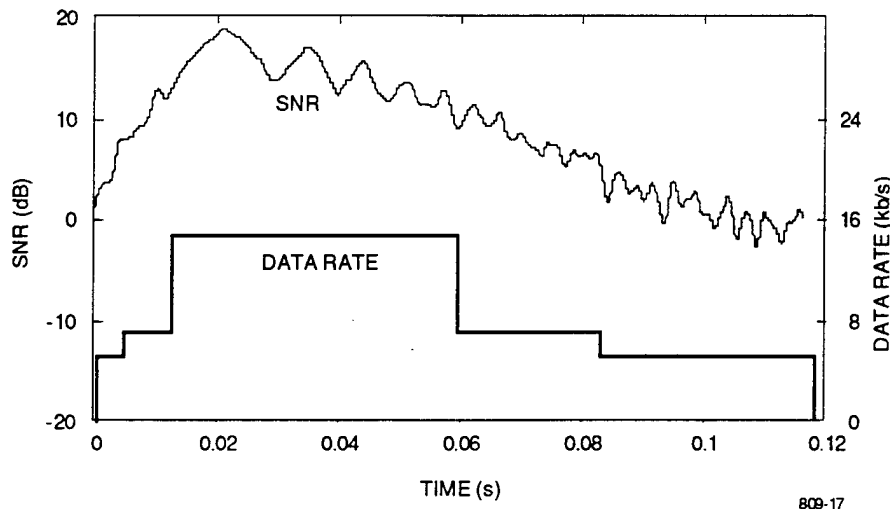
FIGURE 3-19   EXAMPLE OF ASR PERFORMANCE

Feedback Adaptive Variable Rate (FAVR). The FAVR system is a particularly attractive version of the ASR technique designed and tested by Chang and Schilling (1992). In this system, the symbol rate is varied in discrete steps using a fixed rate per packet. Alternate steps sizes are 4/3 and 3/2, giving data rates of 2, 3, 4, 6, and 8 kb/s. Each individual packet is sent at a fixed symbol rate, but the symbol rate between packets can change depending on the SNR at the time. SNR determinations are based on the assumption of reciprocity, but it is also assumed that techniques such as null steering and noise canceling are used to minimize the effects of differences in local noise and interference between the remote and base sites. As was shown in Figure 3-15, the FAVR process for automatic identification of the symbol rate eliminates the need to communicate bit-rate information. This process requires a fairly involved set of demodulators and decision hardware to determine the correct bit rate and pass on the valid data. The timing recovery circuits of the three separate demodulators must also be flexible enough to lock on to the variety of symbol rates.

Two-Step Variable Rate. A simpler rendering of the ASR technique that uses a two-step variable rate has been proposed by Westinghouse (Dave Proson, private communication). In this system, the two rates and the time to switch between them must be determined by some version of the optimal-fixed-rate decision process already described. Figure 3-20 shows an example of a two-step variable rate system that we simulated to illustrate its performance. This system must rely on the same type of prediction of maximum signal power and decay rate proposed by Abel (1986). Also, it requires the same types of hardware that would be used in the FAVR or other more fully variable ASR system, but it clearly cannot perform as well and thus is not likely to be cost effective.

33
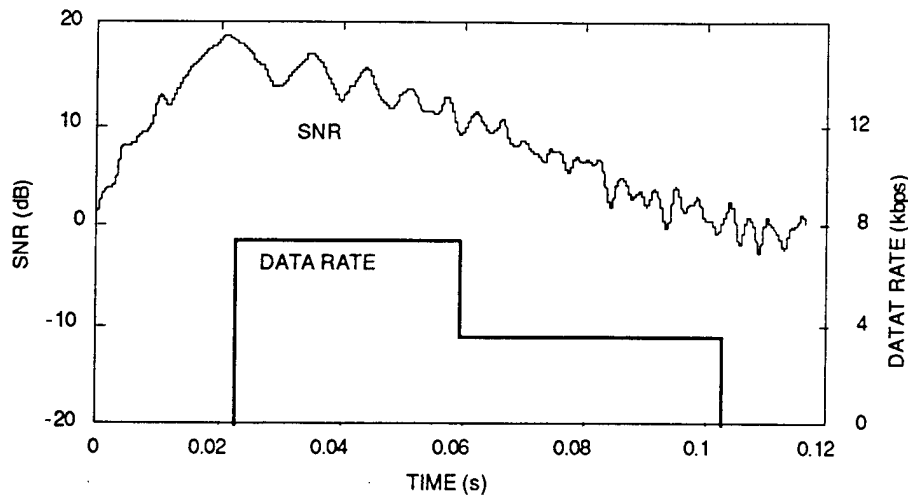
FIGURE 3-20   EXAMPLE OF THE TWO-STEP RATE

Adaptive Symbol Constellation (ASC). Whereas ASR techniques change the symbol rate and bandwidth, ASC techniques change the size of the symbol set in response to variations in SNR but maintain a constant symbol rate at the maximum level allowed by the bandwidth. ASR techniques could optimize both throughput and waiting time for MBC systems if they were not limited in their bandwidth. However, within the available bandwidth of 16 kHz for a 20-kHz channel spacing, the bandwidth efficiency of ASC techniques give them a clear advantage. M-ary PSK modulations are good candidates for the underlying modulation of an ASC system, because they maintain a constant bandwidth as M (the signal set size) increases, unlike M-ary FSK systems. An ASC system might have choices for M of 2, 4, 8, and 16 to provide modulations of BPSK, QPSK, 8-PSK, and 16-PSK. The demodulator for this system must be flexible enough to decode modulations with various symbol set sizes, which implies a somewhat complex slicer that can set the symbol constellation boundary limits depending on the order of the modulation currently being sent. A complicated carrier-recovery circuit will also be needed if decision-directed recovery is used to recover a reference carrier phase because the circuit must also be able to set the predicted boundary limits for the incoming signal.

Jacobsmeyer (1992) has described and evaluated an especially promising ASC system that includes adaptive trellis-coded modulation. As M increases for an M-ary PSK system, the number of bits per symbol increases as

$$\text{bits per symbol} = \log_2(M).$$

The associated data rates are then integer multiples of the symbol rate. Typically, the symbol rate is chosen to minimize the wait time between messages and is limited by the bandwidth available on the channel. Jacobsmeyer's adaptive TCM system uses a set of TCM signal constellations to vary the data rate of the system. It uses an M-ary PSK line coder for QPSK, 8-PSK, and 16-PSK and a convolutional encoder to form the trellis-code modulator. One convolutional code (a 1/2 rate 64-state code with K=7) is used for all three line coders to simplify the design of the modulator. In the higher order modulations (8-PSK and 16-PSK), the added bits are sent uncoded to the line

34

coders, and they cause parallel transitions in the trellis state diagram. To minimize increased error in decoding the parallel transitions, the line coder needs to be designed so that the Euclidean distance between symbols with parallel transitions is maximized (Lee and Messerschmit, 1988). Figure 3-21 shows a block diagram of the modulator. To decode the convolutional code, Jacobsmeyer recommends a slightly modified conventional Viterbi decoder using soft decoding.
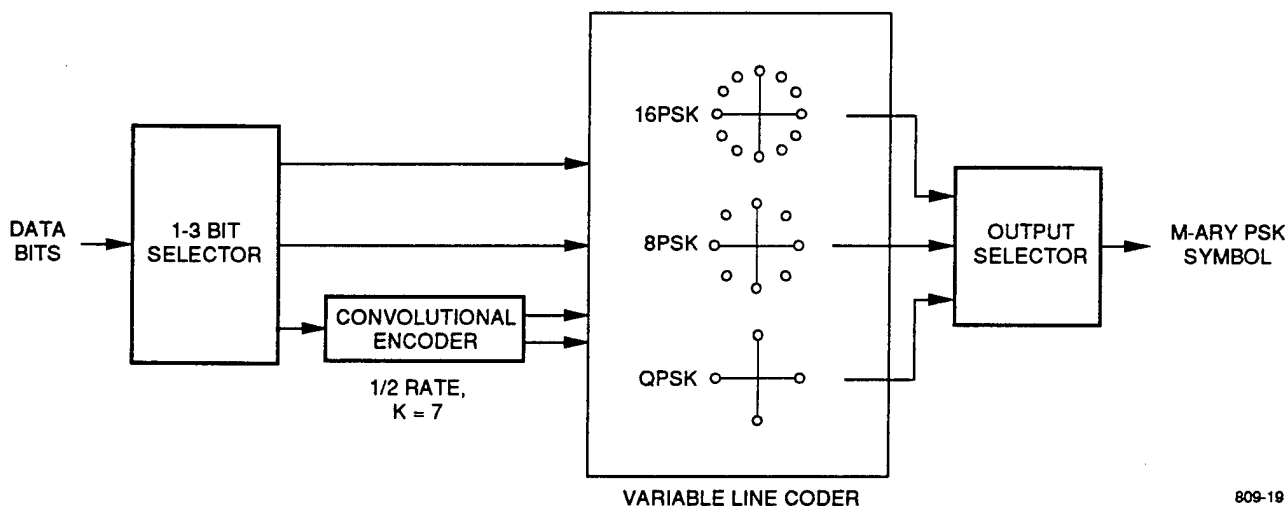
FIGURE 3-21   ADAPTIVE TRELLIS-CODED MODULATOR
(adapted from Jacobsmeyer)

3.2.3 Simulations and Evaluations

To evaluate the above ADR techniques, throughputs were simulated using Matlab and the SRI channel model for a representative ASR system and using the 8-kb/s DBPSK system as a standard. It was assumed that all systems used the same sampling rate and their appropriate technologies (such as variable bandwidth filters for ASR). The ability to determine SNR and to communicate bit-rate information was also assumed to be the same (and optimal) for all the methods. This assumption was made because the method of varying the actual data rate was the key factor in judging the various systems.

Results of the simulations and estimated performance gains are shown in Figure 3-22. Except for the simulated ASR case, all the results shown were calculated from values reported by Jacobsmeyer (1992). The graph shows that adaptive TCM (ATCM) performs better than the other techniques.
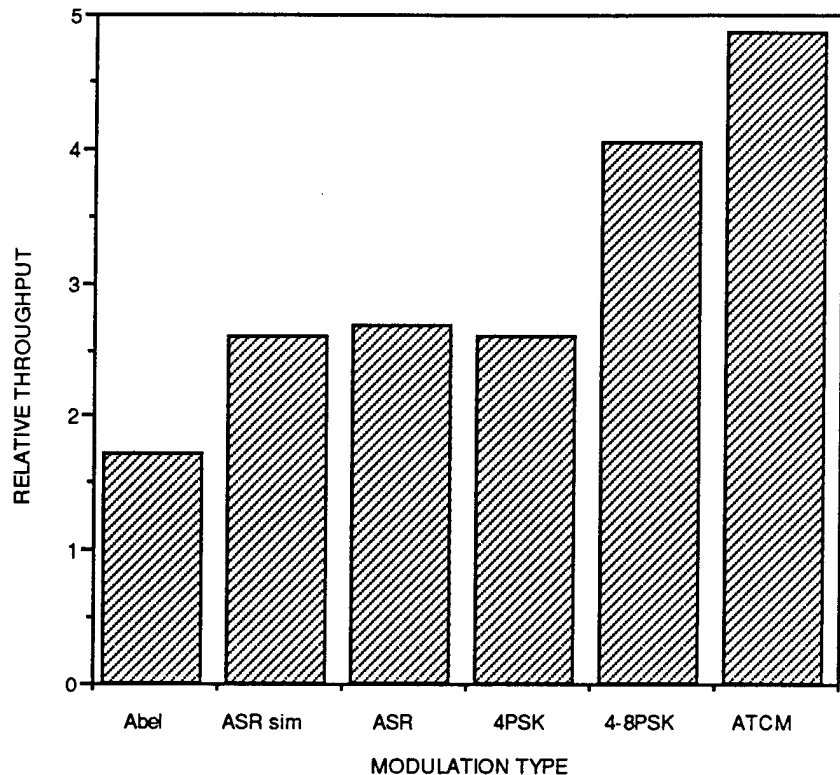
FIGURE 3-22 RELATIVE PERFORMANCE OF VARIOUS
ADR TECHNIQUES

We have not simulated the FAVR system, so it is not included in Figure 3-22. However, Schilling et al. (1991) have also reported the results of a field test of the FAVR modem over an MBC path from Anchorage to Kotzebue, Alaska, and they show improvement by a factor of 3.5 over a conventional fixed-rate modem. The modems were tested both in the field and in the laboratory using a meteor-burst channel simulator. The FAVR modem used a 40-kHz bandwidth and variable rates between 32 kb/s and 90 kb/s. The FAVR modem also used forward error correction, trellis coding, and nonlinear equalization. The fixed-rate modem operated at a data rate of 8 kb/s and used a bandwidth of 15 kHz. Thus, the better performance of the system with the FAVR modem is a result of more than the change from a fixed-rate to an adaptive-rate system. However, the results are impressive and show the performance that can be achieved using ADR techniques.

3.2.4 Recommendations

It is clear that some type of ADR technique should be included in the new Federal standard for an advanced MBC system. Although ADR will add complexity, it will be worth the investment because of the payoff in increased throughput. The best ADR technique studied here is adaptive TCM, so it is recommended for the baseline design of the advanced MBC system. However, the following quotation from Jacobsmeyer (1992) is pertinent.

36

Of course, the ideal adaptive scheme for the band limited channel would combine a bandwidth-efficient technique like adaptive TCM for high signal-to-noise ratios and a power-efficient technique like adaptive symbol rate for low signal-to-noise ratios. The performance of such a hybrid scheme is not investigated in this paper and is left for further research.

To summarize the results presented in both Sections 3.1 and 3.2, we recommend that the modulation for the advanced MBC system be ATCM using M-ary PSK with TCM-QPSK as the lowest order. The convolutional code for TCM-QPSK should have rate 1/2, K=7, and polynomials G0=171 octal and G1=133 octal. The system should also include an appropriate ARQ-FEC protocol, including matrix interleaving, which requires retransmission of data only when errors cannot be corrected.

3.3 Adaptive Antennas

If an MBC system is to take full advantage of the opportunities for increased throughput provided by the advanced modulations discussed above, it will be necessary to operate with an SNR that is as high as can be achieved under the practical constraints imposed by the intended application of any particular system. In most situations, it will probably be more cost effective to increase antenna gain than to transmit a higher power to achieve the desired SNR. Thus, the various options that are available for increasing the gains of the transmitting and receiving antennas are considered here.

3.3.1 Fixed-Beam Alternatives

Traditional meteor burst systems have used moderate-gain antenna elements such as Yagis that are pointed in the general direction of the station expected to complete the link. The broad azimuthal coverage—over about 60° or more—then includes all possible meteor trails that can link the two stations. In some cases, vertical and/or horizontal arrays of these elements are used to provide coverage with higher gains in the more limited spatial regions where usable meteor trails are most likely to form. Illumination of the hot spots offset by about 100 km on either side of the great-circle propagation path is an especially effective technique of this sort.

Various elaborations of the single fixed beam have been suggested to further improve system performance. The place where the specular scattering events can be expected to reach a maximum on a statistical basis can be predicted as a function of station latitude, time of day, and season of the year. SAIC (1992) has thus suggested that the antenna beam be steered from time to time to follow the location of this region. Because the beam is to be steered using analog methods without feedback from the receiver, the effectiveness of this technique depends entirely on the validity of the prediction model. Another approach is to form multiple simultaneous fixed beams, again using an analog beam-forming system, such as a Butler matrix, to provide a fan of beams to cover several of the most likely hot spots. Whichever beam is found to contain the meteor signal at a given time can then be used to complete the link.

The multiple-beam approach has been used by the Pegasus Message Corporation (now defunct) and more recently by Meteor Communication Corporation (MCC) in Kent, WA. The Pegasus antenna had an array of horizontally and vertically polarized Yagis for 12 azimuth-look directions and 4 elevation directions. MCC has implemented systems with four beams fixed in azimuth, and more recently has discussed systems with 16 beams (Mawrey et al., 1992 and

37

Larsen et al., 1992). A receiver and demodulator are provided for each beam port, and whenever a beam is observed to have a high SNR, its signal is processed for the duration of the meteor trail. Multiple receivers are necessary because it takes too long to scan a single receiver through the multiple beam ports within the limited duration of the trail. Because these beams are fixed, the antenna gain will be down about 3 dB or so from the maximum array gain when the meteor trail occurs midway between two beams and, of course, any fixed-beam receiving antenna will be susceptible to interference from any sources of radiation within line-of-sight propagation range. However, the performance of fixed-beam systems should generally be quite good, and can be expected to offer distinct improvement over the performance of systems with broad-beam antennas.

3.3.2 Retrodirective Array

An analog technique for adaptive beamforming has recently been patented (U. S. Patent Number 4,985,707 on January 15, 1991) by BroadCom Inc., in Mahwah, New Jersey. Their antenna is retrodirective in the sense that when a pilot signal is received, a beam is formed automatically to transmit back along the path of the received signal.

An early example of a retrodirective antenna was developed by Van Atta (L.C. Van Atta, "Electromagnetic Reflector," U. S. Patent 2,909,002, October 6, 1959), and another early discussion of the concepts involved was provided by Skolnik and King (1964). Figure 3-23
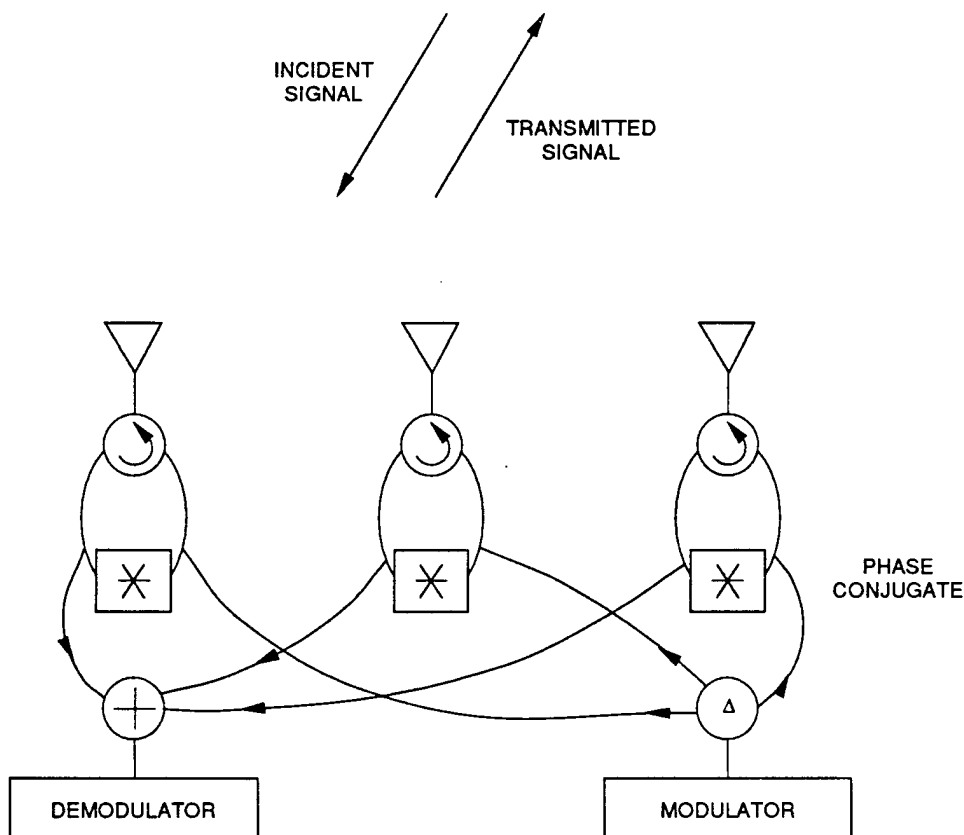
779-5R

FIGURE 3-23   TYPICAL PASSIVE RETRODIRECTIVE ANTENNA ARRAY

38

shows a diagram of a typical, passive, three-element, retrodirective antenna array. The antenna elements have essentially omnidirectional radiation patterns. Conjugate phase networks (depicted in the figure by asterisks) follow the elements and use the interelement delays to force the transmitted signal to be directed back toward the received signal source.

Figure 3-24 shows the BroadCom implementation of one of the retrodirective loops and its associated phase-lock loop in a retrodirective array in more detail. BroadCom uses active components that allow them to mix, modulate, and amplify signals and to transmit and receive on different frequencies. After acquiring the pilot signal from the link transmitter, the phase-lock loop for each element locks to the phase of the received signal, and the array focuses the beam in the direction of the signal, resulting in increased antenna gain and improved link margin. Thus, the retrodirective antenna receives a signal from any portion of the sky above the horizon and transmits a new modulated signal back along the same path, but at a new frequency.
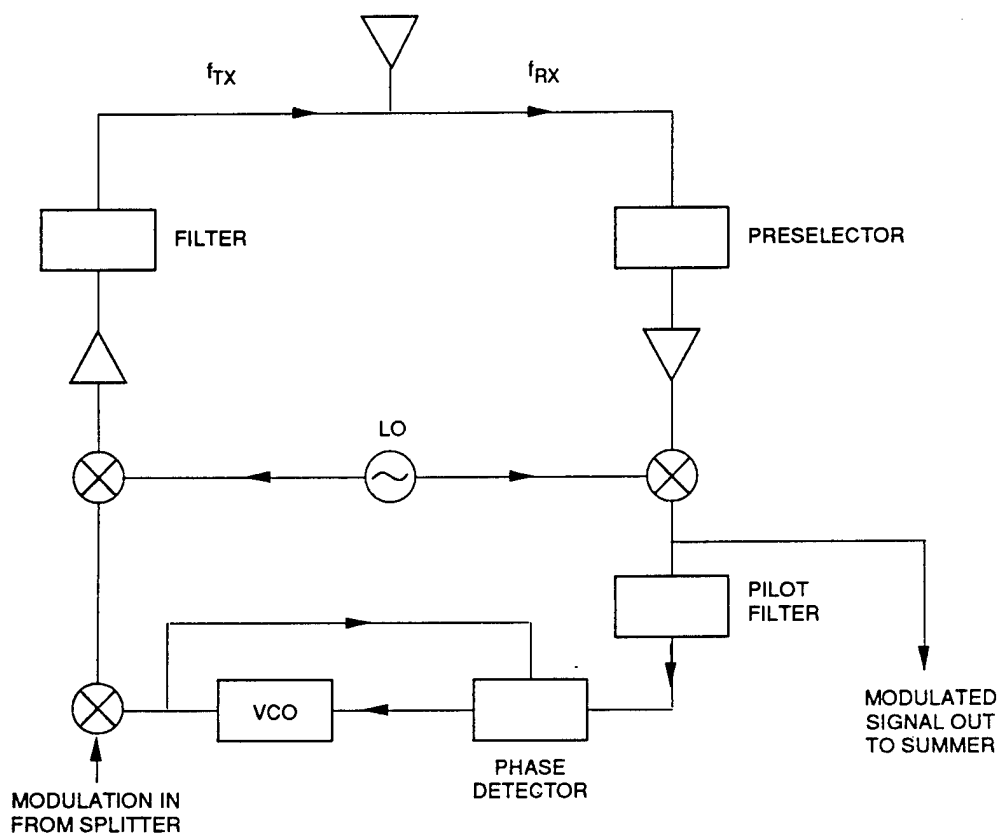
FIGURE 3-24 BROADCOM RETRODIRECTIVE LOOP

Although we are not aware of any experimental data that demonstrate the performance of the BroadCom retrodirective antenna array in actual MBC applications, we have no reason to doubt that it is capable of performing essentially as advertised. However, it does have two relatively minor drawbacks that might limit its effectiveness. First, it requires the use of a narrow-band pilot signal to establish the initial link and set the phase-lock loops. This pilot signal, unique to this system is incompatible with Proposed Federal Standard 1055, but the new standard could be written to include an option for a pilot signal. A second potential drawback is the susceptibility of the system to interference from other sources in the frequency channel within line-of-sight

39

distance of the retrodirective system. The phase-lock loop might be captured by the interfering signal, making it unavailable for the meteor burst signal.

3.3.3 Digital Systems for Real-Time Performance Optimization

Adaptive digital beam-forming and nulling are now performed routinely in a number of different radar, communication, and signal intercept systems, so that the transfer of this technology to MBC systems should be possible in a straightforward manner with little technical risk. The speed of digital processors is so high that beams and nulls can be formed adaptively in times that are negligible compared with the acquisition times for MBC links (typically on the order of 10 ms or more). Also, the cost of the components of digital systems is now so low (and is still decreasing) that there is little if any advantage in using analog techniques to achieve the same gain for the antenna beam. Thus, because of the increased operational flexibility provided by digital techniques, and because of their unique capability to improve performance by adaptively nulling any interfering signals that are received, adaptive digital systems are the technology of choice for advanced MBC systems.

An adaptive MBC antenna system is now being built and tested by the Westinghouse Electric Corporation under Project SUNFLASH, sponsored by the Defense Advanced Research Projects Agency. Figure 3-25 shows a block diagram of the Westinghouse system (R.C. Brown, D. Proson, and K.S. Wheeler, private communication). They use a 2x4 Yagi array (each Yagi with 7 elements), but the array is used only for receiving. Each element is followed by a low noise amplifier, a receiver/downconverter, and an analog-to-digital converter (ADC) in the usual way. The performance of this system measured in an actual meteor burst application is not currently available, but we have no reason to doubt that the system will perform as expected.
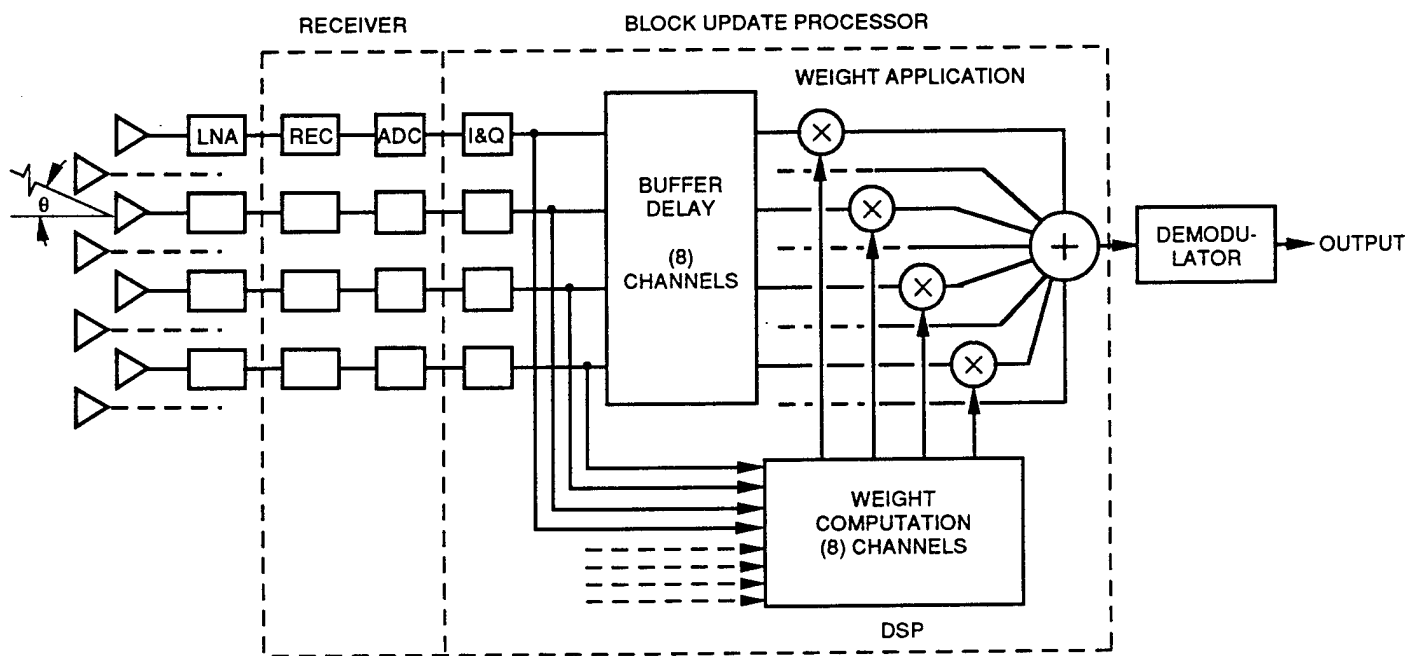
FIGURE 3-25 WESTINGHOUSE ADAPTIVE MBC ANTENNA

40

3.3.4 Recommendations

For use in the prototype baseline MBC system described in Section 4, a simple, general-purpose, adaptive array has been designed here as shown in Figure 3-26. Three orthogonal crossed dipoles configured as a tripole (Compton, 1981 and 1988) are used as the basic element of the 4×4×2 array, and the three vertically arrayed pairs of the dipoles making up these tripoles are hard-wired together to reduce the number of receiver/ADC units required to 48 (4×4×3 = 48). The advantage of using an omnidirectional element instead of the traditional Yagi is that it permits complete versatility in networking applications where the payoff comes when each site can link instantaneously to multiple surrounding sites (as discussed in Section 3.4). The tripole also has the advantage that it can adapt its polarization in any way that may be needed for each meteor trail. In the case of the array shown in Figure 3-26, the array gain of the 16 tripole-pairs is roughly comparable to that of the eight 7-element Yagis used by Westinghouse.

Although adaptive polarization systems have not been used for MBC applications before, this capability is expected to have a significant payoff for at least three reasons. First, the radar cross section of any given meteor trail can be expected to depend on polarization, and probably is greatest when the polarization of the incident wave is aligned with the length of the trail. Second, Faraday rotation of the plane of polarization of the signal as it travels along the propagation path, although probably less than about 20° in most situations (Nes, 1985; Brown, 1991; Cannon, 1986), can be expected to cause the polarization that arrives at the receiver to be somewhat different
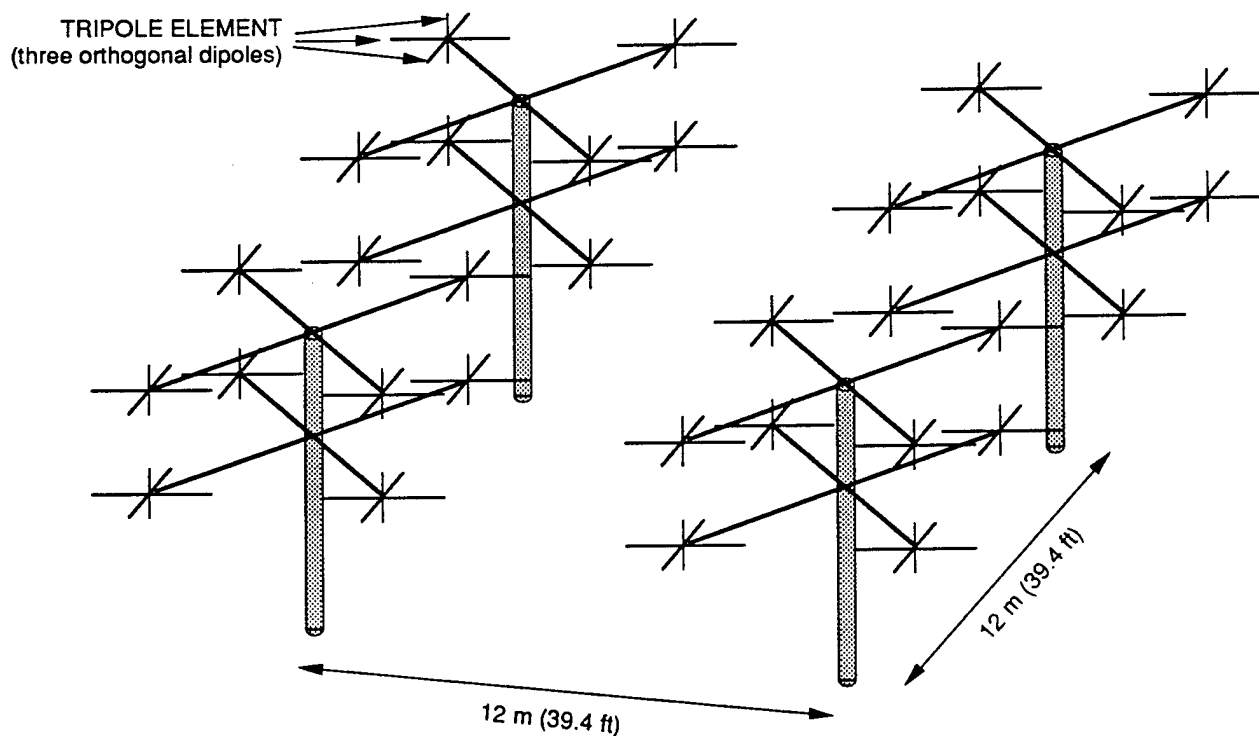
FIGURE 3-26 PROTOTYPE MBC ADAPTIVE ANTENNA ARRAY

41

from that leaving the transmitter, thus causing some mismatch loss. Finally, polarization is another dimension that is very valuable for adaptively suppressing interference from unwanted signals. It is not possible to define exactly the performance improvement that can be expected as a result of an adaptive polarization capability, but 3 dB is a plausible estimate. Measurement of this improvement during the testing program for the prototype system will determine whether or not an adaptive polarization capability is a cost-effective feature for an advanced MBC system.

For the prototype system, beam-forming will be used for both transmitting and receiving. Full-duplex operation will require adequate isolation between the transmitter and receiver, and whether this is achieved by including duplexers between the antenna elements and the receivers for a single array or by building a second array for the transmitter will depend on the relative cost of these two options (and possibly on space availability). Each of the 48 dipole pairs (3 each in the 16 tripole pairs) will be connected to a 100-W amplifier, so the total transmitter power for the system will be 4.8 kW. Steering of the transmitter antenna beam will then be done by adjusting the phase of the output of these individual final amplifiers. Although a 100-W amplifier will be attached to each orthogonal element, the effective radiated power of each tripole pair in any arbitrary direction (in the upper hemisphere) will be only 100 W at the maximum gain of the element (about 11 dBi, the same as a dipole pair vertically disposed over a ground plane).

The prototype MBC system is intended to operate as follows. While waiting for a suitable meteor trail to form so a link can be established, a station will transmit omnidirectionally at low power (100 W) on only a single turnstile-pair. (A turnstile is formed with the two horizontal dipoles of the tripole, and a turnstile pair is formed by connecting the four horizontal dipoles of two vertically stacked tripoles.) In spite of this reduction of transmitter power (P_T) and transmitter antenna gain (G_T) by a factor of 16 during acquisition from the full system capability (for a total reduction of $P_T G_T$ of about 24 dB), it will still be possible to establish the link. It will be possible because the radar cross sections of meteor trails typically are at least 10 to 15 dB bigger at their peak (near their beginning, during acquisition) than at the end of their useful lifetime (as measured with a constant antenna gain). For our system, the additional 24 dB of $P_T G_T$ will be switched into the system immediately after the link is established to further improve the link margin. G_T cannot be increased during the acquisition phase because the unknown location of the next suitable meteor trail requires that the antenna radiation pattern be omnidirectional. However, P_T can be increased to reduce the waiting time between trails to any desired level, discussed below.

The effect of increasing $P_T G_T$ after acquisition of the trail will be to increase the duration of the meteor burst signal above the detection threshold; it will not reduce the waiting time between trails. However, the waiting time for even the low-power, low-gain system will be adequate for good performance. In particular, as shown by Ames (1984), the waiting time for a 189-dB system will be 40 s or less over distances of about 600 to 1500 km between stations. A 189-dB system is one that can operate with a basic transmission loss of 189 dB, as can be seen by rearranging the bistatic radar equation (in dB form) to give

$$L_b = P_T + G_T + G_R - SNR - B - kT_0 - F$$

42

where

L_b = Basic transmission loss (including geometric spreading, scattering from the meteor trail, and absorption), dB

P_T = Transmitter power, dBW

G_T = Gain of transmitting antenna, dBi

G_R = Gain of receiving antenna, dBi

SNR = Signal-to-noise-ratio required for detection, dB

B = Bandwidth, dBHz

kT_0 = -204 dBW/Hz

F = Receiving system noise factor, dB.

In our case, for the acquisition mode, we have P_T = 100 W = 20 dBW, G_T = 11 dBi (for a single turnstile pair), G_R = 23 dBi (for 16 tripole pairs), SNR = 10 dB (assumed detection threshold), B = 20 kHz = 43 dBHz, and F = 16 dB (determined by galactic noise at 50 MHz), which gives L_b = 189 dB. It might be desirable to increase the transmitter power on the acquisition turnstile to 200 W or 400 W to reduce the waiting time even further. In fact, P_T could be increased on the four center tripole pairs in the array to give an amplitude taper to somewhat reduce the side lobes of the transmitter array gain pattern, and this increase on the pair used for transmitting the acquisition signal would then decrease the waiting time to perhaps as low as 10 to 20 s.

In summary, we recommend that the baseline advanced MBC system have a 4x4x2 array of tripole antennas capable of adaptability in beam steering, nulling, and polarization.

3.4 Network Topology and Routing

One of the primary shortcomings of MBC systems is the limitation on throughput caused by the short trail durations and the long waiting times between suitable trails. Networking can help alleviate this problem by providing alternative paths. Although every alternative path is subject to the same limitations on throughput, the conglomeration of paths will achieve a greatly improved throughput. Also, because the duty cycle for each path is so low, and consequently the RF and computer resources at each site are greatly underutilized most of the time, the increased performance provided by networking can come at virtually no cost. Networking can help only in situations where more than two MBC stations are required; the more stations there are, the more networking can help.

Existing MBC systems of more than two stations use rudimentary network designs in which either a single master station controls multiple remotes by polling, or fixed routing of user data is established among stations. However, the processing power and affordability of computers today allow more flexible and efficient network architectures for advanced MBC systems, so the question arises as to what specific network architecture and protocols should be used in these systems. To answer this question, we first establish that networks can be of great benefit to MBC systems. We then show how the existing proposed Federal standards for MBC can be used and complemented with new protocols for networking purposes, and finally we discuss the technical problems for which new solutions are needed before advanced networked MBC systems can be implemented and used. The development of advanced networking techniques will then be able to improve the effectiveness of MBC systems substantially in such civilian and military distributed applications as command communications, sensor networks, internetwork order wires (in which

MBC could provide an independent channel to help control or unsnarl networks using other propagation methods), and the reconstitution of MBC systems after failures.

In this study, we consider a layered architecture based on the ISO model for open systems interconnection (Zimmermann, 1980), which permits us to assume that Proposed Federal Standards 1055 and 1057 (or future extensions and modifications thereof that become the advanced standards) can be adopted to support link-level issues, and focus on other networking concerns that are important in advanced MBC systems, but which should remain transparent to conventional (nonnetworked) MBC systems.

3.4.1 Value of Networking

The basic question in determining the extent to which networking will pay off for MBC is whether or not the benefits are worth the cost. This question is complex because the advantages of networking depend on user needs, user applications, and the network topology. We show here that the provision of advanced networking techniques for MBC will be cost effective in many situations, especially those requiring increased throughput as well as robustness and reliability. Because of the complexity of the issues involved, we base our conclusions both on a qualitative analysis of the issues and on the quantitative results obtained with a simple simulation model of an advanced MBC system.

The hardware and software costs incurred in providing advanced networking functionality in MBC systems are negligible compared with the inherent costs of building and operating remote and master stations. Although initial software development may be costly, if the new Federal Standards for networking define the proper architecture, they should not be excessive. The most sophisticated router boxes cost only around $12,000 (roughly 5 to 10% of the cost of a master station) and support a large number of communication protocols (e.g., Ethernet, token-ring, FDDI, TCP/IP, the OSI protocol suite, DECNET Phase IV and V, XNS, Novell IPX, Banyan VINES, #COM 3+, AppleTalk Phase 1 and 3, Apollo Domain, and SDLC, as can be seen, for example, in Datasheet, 1992). Needless to say, far less capable hardware and software would be needed for advanced MBC systems, for two main reasons:

- The low data rate in an MBC system lends itself to relatively few applications compared with the numerous ways existing networks and internets are used.

- Considerably more time would be available for networking software to respond in MBC systems than in traditional systems, because meteor-burst trails are intermittent with waiting times between trails on the order of tens of seconds.

From the above, it follows that a 68030/68040 or 386/486-based computer, which costs only a few hundred dollars, should be more than adequate to support networking at a master station. For remote stations, even lower-performance computers will likely suffice, as each remote will typically have to handle only small amounts of data. If the computer hardware at an MBC station is also used for other purposes (such as adaptive antennas or modulations) not related to networking or communications, the incremental cost of networking will be negligible.

Advanced networking functionalities can improve the performance of an MBC system by providing more robust connectivity among stations, transparent recovery from failures, congestion control, and efficient routing of data (Bertsekas and Gallager, 1992). The simplest MBC networks consist of a series of remote stations controlled by one or more master stations. Current MBC

systems typically operate only in the simplest mode, in which a single master station controls a few remote stations (Kokjer and Roberts, 1986). Even in this case, if the number of remote stations and the amount of traffic from each occasionally results in data rates that exceed the capacity of a master station, additional master stations will be needed, perhaps with each remote station nominally assigned to one master station, as illustrated in Figure 3-27. (The capacity of a master station is set by the waiting time between bursts and the duration of the bursts as well as by the number of its remote stations, the limitation being that the master station can communicate with only one remote station at a time on a single operating frequency.) The configuration in Figure 3-27 shows alternate links to another master station with dashed lines.
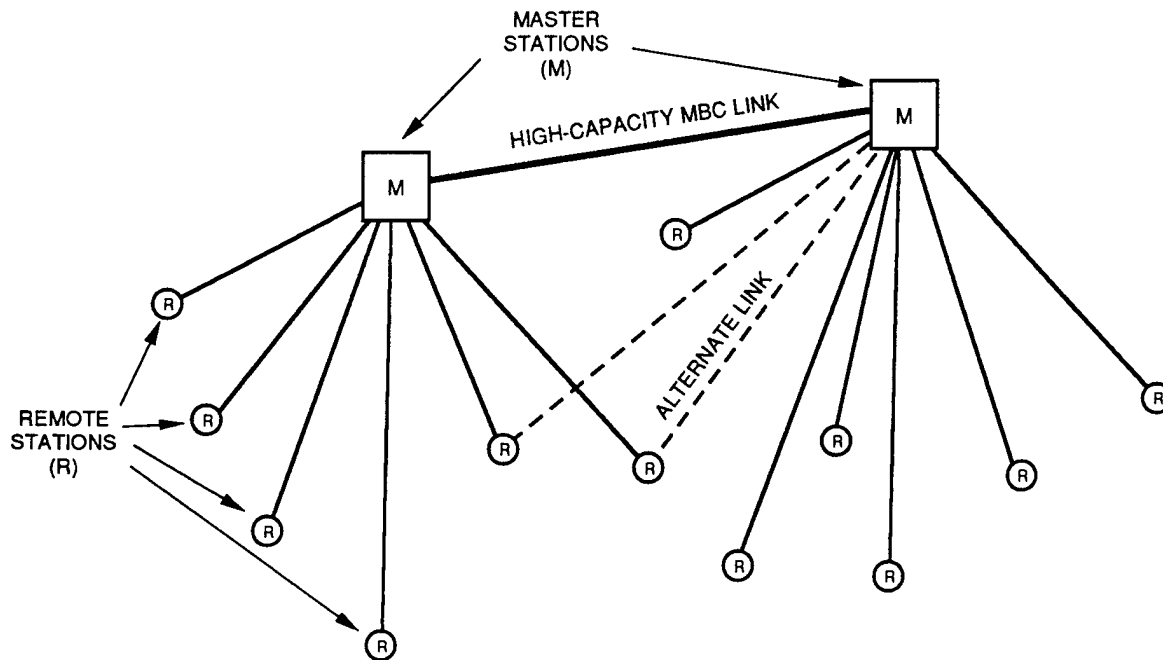
808-1R

FIGURE 3-27   REMOTE STATIONS WITH TWO MASTER STATIONS

If data arrive in bursts, the arrangement with remote stations served by only one master station is inefficient because alternative, underutilized channels cannot be called on to handle a large, transient data load if a master station is already loaded to capacity. On the other hand, the alternative links would be available if the system were configured with multiple master stations to connect to the same remote stations as well as to each other. Throughput could then be increased by using alternative paths, because links between master stations typically would have greater capacities (because of higher antenna gains and transmitter powers) than links to remotes. This gain in throughput is possible even though using a second master station to relay traffic adds an additional hop. For example, suppose that a network contains 40 remote stations and two master stations, and that each master station can handle up to 30 remote stations under typical conditions, but that each master station usually handles only 20 remotes. If a burst of data arrives at one or more remotes that normally use master station A, it may be advantageous to relay some of the data through master station B to make use of its excess capacity. If the hardware (e.g., adaptive antennas) allows this alternative routing, throughput will be increased (or equivalently, the delay

45

for a given message will be decreased) by making use of the additional path. With two master stations, this capability can increase throughput by somewhat less than a factor of two (less, because network control uses some of the throughput and because the second path has two hops instead of one). Providing such a capability would require network-control protocols that can pass control information describing queue lengths between stations and negotiate a control strategy based on that information.

More complex MBC networks will employ multiple interconnected master stations providing multiple paths to one or more destinations. Such connectivity can be exploited for several purposes, ranging from providing the necessary geographical coverage to reducing end-to-end delay, increasing throughput, or increasing reliability and survivability. In the multihop case, it is clear that providing alternative paths increases survivability and reliability over fixed-routing strategies. However, it is not clear that a particular routing strategy can provide better performance than basic flooding of data. To obtain additional insight into the benefits of basic network functionality, we have run several simulations of MBC networks.

The multiple-master-station scenario described above suggests that adaptive routing could constitute a key functionality for advanced MBC networking. A large number of adaptive routing algorithms can be considered for MBC systems, including shortest-path routing (with the length of the path reflecting any of a number of performance measures); multiple shortest paths; shortest maximally disjoint paths; and minimum spanning-tree algorithms for efficient multicast (Bertsekas, 1991; Garcia-Luna-Aceves, 1993). These algorithms can provide considerably better results than can be achieved by simply flooding messages to all available nodes, and can in some cases provide higher throughput than would be achieved by using a single fixed route alone. To obtain some quantitative basis for comparing adaptive routing schemes, we simulated several different candidates that might be implemented in a routing protocol for MBC systems. In our previous evaluations of modulations and adaptive data rates, we have used throughput as our measure of performance for the purpose of comparison. However, in the evaluation of various network routing strategies shown here, we use delay through the network as the relevant performance measure. In general, it can be assumed that throughput is inversely related to delay, so this change is not particularly significant. We made it simply for the convenience of using an existing network simulation computer program. In particular, in this simulation we looked at routing strategies ranging from using a single path to the destination to using all paths, good or bad:

- Shortest-path routing (because all links have identical properties, shortest-path routing provides minimum average delay in the absence of congestion)

- Routing to the two best neighbors, i.e., those two neighbors that are closest to the destination (have the shortest distances to the destination of any of the neighbors)

- Routing to the three best neighbors

- Routing to all best neighbors

- Flooding, in which all transmissions are sent to all nodes in the network.

The above routing strategies were modeled for the 16-node model network shown in Figure 3-28, where each circle represents a master station, and links indicate which stations can be connected by a meteor-burst trail. It is assumed that all links have identical properties, and that the four sources on the left side of Figure 3-28 send data to the four destinations on the right. Each source sends the same amount of traffic to each destination. Our simulation assumes that meteor

46

bursts are characterized by an average waiting time of 60 s (assuming a Poisson distribution), that the burst duration is exponentially distributed with an mean of 1.5 s, that the propagation time over each link is 3 ms, and that messages are made up of 100-bit segments, each 40 ms long. Message durations are exponentially distributed, but are quantized in segments, and the mean message duration is 4 segments (160 ms). These numbers are based on typical values for an actual experimental MBC system (Heilman et al., 1989; Rich et al., 1990).

The interarrival time for a message from a given source to a particular destination is defined as the time between the start of one message and the start of the next message. For the simulation, messages were generated with a variety of interarrival times (the times had a Poisson distribution, with a mean that was specified for each computer run). If a segment could be delivered only partially, the simulation placed it on a retry queue for later retransmission. The model also delivered messages in order, and deleted duplicate messages. Duplicates may occur because multiple paths are used or because the channel does not last long enough for an acknowledgment to be received. At any node, incoming messages are routed based on information stored in a routing table that defines the routing protocol being simulated. For each source-destination pair, the table specifies one or more nodes that will receive the message. Each of these nodes in turn will route the messages unless the node is itself the destination for that message. The link models
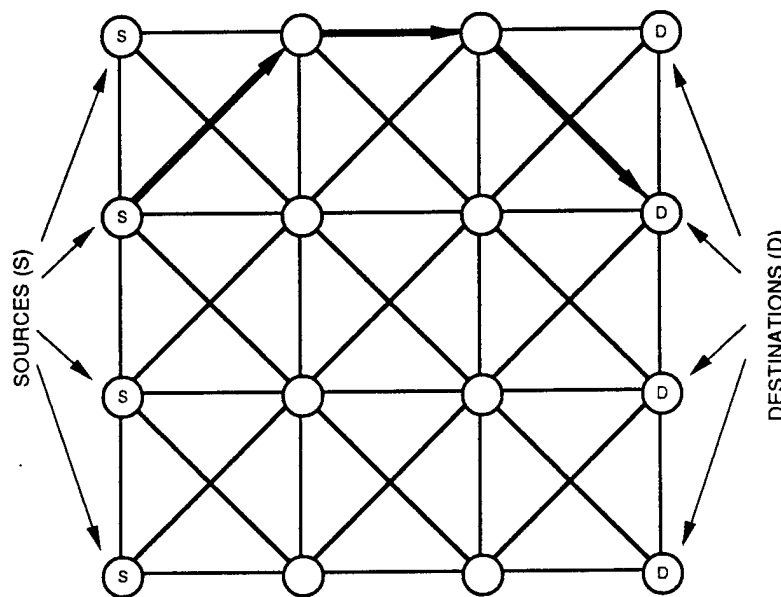
808-2

FIGURE 3-28   A 16-NODE METEOR BURST NETWORK

used in the simulation can support both full-duplex and half-duplex operation. The channel is assumed to deliver messages reliably for an exponentially distributed interval (the trail duration), after which traffic is dropped until the channel becomes active again (when a new trail appears). Messages that would be only partially delivered are assumed to be in error. The traffic source models were configured so that each source generated equal levels of traffic for each destination.

Figure 3-29 shows the results of the simulation runs in terms of delay over a range of interarrival times for new messages. Delay is the sum of all the trail waiting times, propagation times, and queuing times over all the links between the source and the destination for each

message. Because delay is inversely related to throughput, the best routing strategy is the one with the smallest delay. As the figure shows, using all feasible paths provides an advantage over the range of interarrival times simulated, whereas flooding decreases performance. It can also be seen in Figure 3-29 that all routing strategies have essentially the same shape, with delay falling sharply as a function of interarrival time and then leveling out beyond some break point that appears at different interarrival times for different routing strategies. To the right of this break point, traffic density is low enough (interarrival times are high enough) that network congestion and the resulting queuing delays have begun to approach their minimum levels.

There are sixteen traffic generators in these simulations because each of the four sources in Figure 3-28 sends messages to each of the four destinations. Flooding works poorly in the simulated networks because the data created by each source are sent to all adjacent nodes, and congestion increases throughout the network as multiple sources of data compete for the communication resources of all intermediate stations. The congestion increases queuing delays sufficiently to more than offset the reduction in transmission delays achieved by using multiple paths. Using multiple shortest paths provides a reduction in delay compared with shortest-path
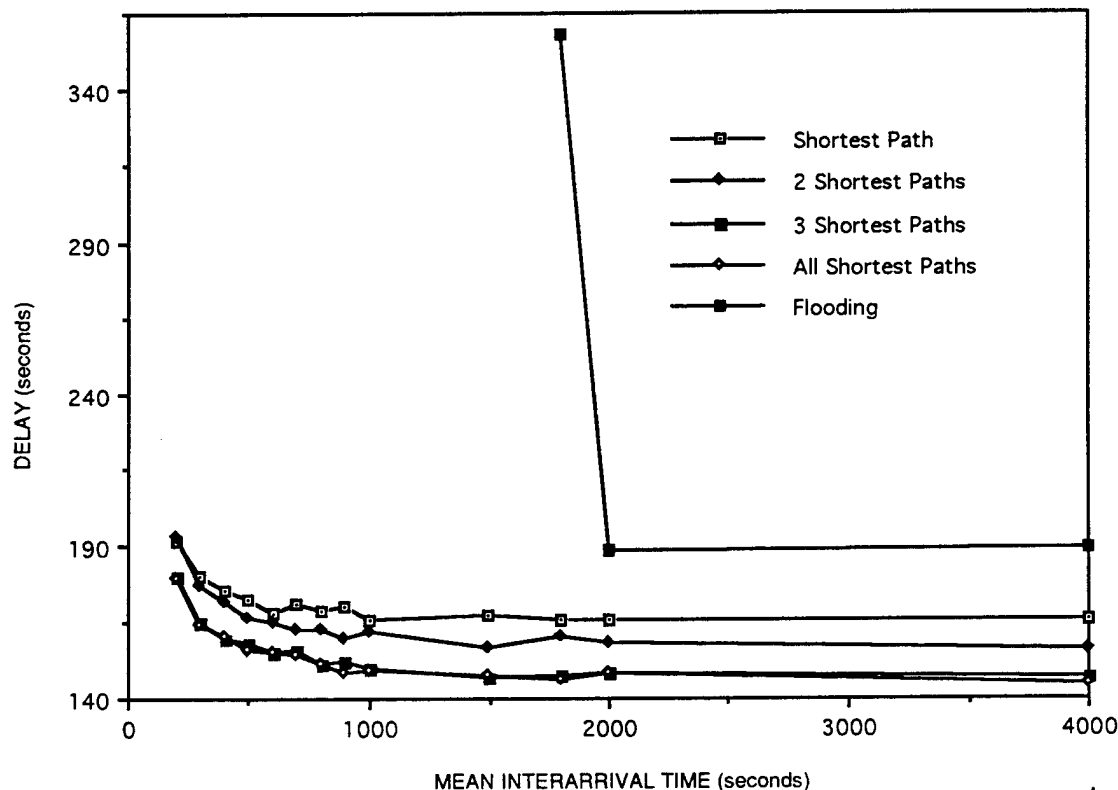
FIGURE 3-29   DELAY AS A FUNCTION OF NETWORK LOAD

routing, because multiple paths are used to forward data from a source to a destination. Because this scheme limits the number of paths used concurrently for a given source-destination pair, it reduces contention for resources and the consequent queuing delays experienced with flooding.

Of course, at traffic levels higher than simulated (that is, for smaller interarrival times), congestion will eventually build up using even the multiple-feasible-paths routing strategy. A way of coping effectively with this buildup would be to split traffic among multiple feasible paths, instead

48

of sending the same traffic over multiple feasible paths; this strategy could improve performance beyond what our simulation results show. In our simulation, we send the same data stream to multiple nodes, thereby providing (in some cases) reduced delay with protection against hardware failures at some intermediate nodes (the number depends on the network topology). Further improvements in throughput will occur if the traffic stream is split up among several downstream nodes, each handling part of the traffic flow. If we neglect additional information needed in headers, we can route traffic in parallel by utilizing n independent paths, which will provide an n-fold improvement in throughput in the absence of congestion from other traffic streams (i.e., with other sources or destinations). Of course, such improvements are topology-dependent, and a particular topology may not provide any alternative paths or independent paths.

In summary, it can be seen in Figure 3-29 that for the simple network simulated here, some form of multiple-shortest-path routing can decrease delay (and improve throughput performance) by about 10 to 20% compared with either fixed routing or flooding. Also, because the computer resources needed for networking should be available as a shared resource with other advanced MBC functions, such as adaptive antennas, this performance improvement should be obtainable at virtually no cost. Although this simple analysis shows that some form of adaptive routing scheme using multiple paths is preferable to brute-force flooding, fixed routing, or simple shortest-path routing, a detailed model will be needed to choose a specific routing scheme, based on the characteristics of a particular MBC network and the applications likely to use the network.

Our simulation results differ from those reported by Hirst et al. (1985). They focused on restricted topologies, in which every node could reach every other node directly, and they assumed very low data rates. Also, although they assumed exponentially distributed waiting times for each link (the waiting time for a suitable trail to become available), they did not take into account the additional queuing delay that will occur at relatively high loads. They point out these restrictions but suggest only that the nodes in an MBC network be controlled by a station responsible for network management, which reflects the technology available in 1985.

3.4.2 The Transition to Networked MBC

Networking should be incorporated into the standards for advanced MBC systems in such a way as to permit an orderly transition from the present generation of MBC systems without overly constraining system and application developers. Thus, an early direction must be set for the way in which communication protocols for MBC networks are organized and developed, and for the type of applications to be supported. To a large extent, the separation of hardware-specific message formats (e.g., those needed for channel acquisition and link-level data transfer) from those needed for higher-level processing (e.g., network software) is the key ingredient in pro-moting an orderly development of MBC networking products. For this reason, an open, layered approach should be taken to the development and implementation of advanced MBC networking. This same approach has been used in every successful protocol architecture, such as SNA, DECNET, TCP/IP, and the OSI architecture for open system interconnect.

With the layered approach, each level of the communication system prepends its own control information, and can usually provide services to multiple users. Related services are grouped into particular layers, and lower levels pass data between peers in such a way that any transformation of information (e.g., encryption, FEC encoding, data compression) is undone before the data are delivered. In addition, a level-n protocol is assumed to know nothing about the structure of the data sent by higher level protocols. As a result, it is relatively easy to add new protocols to the

network because a protocol inserted into level n will not require changes to software implementing level n-1 or below. The open component of the approach simply means that each key protocol of the architecture is made into a public-domain standard, so every vendor can implement the protocol. Therefore, an open and layered protocol architecture will permit system vendors and developers to write and introduce networking standards in an orderly fashion, without unduly constraining their ability to sell their unique MBC products for particular applications.

Once a layered approach is adopted, a number of decisions must be made for the development and introduction of MBC networking standards, namely, the type and number of protocols to be used, and the mix of services required in an MBC network. There are advantages to following existing networking standards in the introduction of protocol standards for MBC networks; one clear advantage is that it would be simple to port applications to MBC networks whenever this may be desirable. However, our experience with other systems suggests that taking a protocol designed for a given communication environment and simply scaling its operating parameters to match a new environment will not work when the two environments have drastically different capabilities. For example, when Mathis et al. (1986) attempted to port packet-radio protocols to SINCGARS radios, they found (from simulations) a number of problems that required some redesign before success could be achieved. Because of the unique characteristics of meteor-burst links, there are several features in communication protocols widely used today that similarly must be completely redesigned.

In addition to the need for some redesign, the current Proposed Federal Standard 1057 for MBC makes assumptions about the mix of network-level services that may lead to difficulties in the future. For example, current network standards for terrestrial internets provide two basic classes of network-level services: those that provide reliable delivery and those that provide unreliable delivery. Both types of delivery have advantages depending on the application to be supported, and it is conceivable that both types of services can be useful in the same network. (Unreliable delivery is acceptable, for example, where information has value only if it is the most recent available. If a data packet is delayed or lost or in error, it becomes completely unimportant and can be purged as soon as a more recent packet is received.) The problem with Proposed Federal Standard 1057 is that it is not clear about the use of end-to-end acknowledgments. The standard says that

> An End-to-end Acknowledgment (EACK) is typically generated by the last master station in the chain of delivery, upon confirmed delivery of a message to a remote station. Remote stations do not generate EACKs. End-to-end Negative Acknowl-edgments (ENAKs) can be generated by any master station and signify that a message is not capable of being delivered.

As stated, it is not clear under what circumstances an EACK is generated (the word "typically" implies that the last master station before a remote does not necessarily generate an EACK, and no protocol is provided to indicate which station is responsible under which circumstances). As a result, it is not obvious whether or not the standard calls for reliable or unreliable network-level service. This ambiguity may cause difficulties for some applications. If the specification is vague, applications will have to make worst-case assumptions and will generate their own, sometimes redundant, end-to-end acknowledgments.

50

3.4.3 Technical Issues for Design

Although the OSI and TCP/IP architectures for open system interconnection contain a large number of protocols at various levels (Bertsekas and Gallager, 1992), the basic functionality needed to establish an advanced MBC network will be required primarily for the link, network, and transport layers. These layers must be emphasized because they have the most impact on performance and topology control. (A session-level protocol, for example, may be quite complex because of the need to coordinate the activities between two separate systems, but it will induce little overhead beyond what would be required simply to transfer user data, except perhaps for some terminal-based interactive applications that are not likely candidates for MBC systems.) The functionality at these three layers can be summarized as follows:

- The link level is responsible for moving data between neighboring nodes.

- The network layer handles routing and congestion control. Delivery may be reliable or unreliable, depending on network characteristics. (Transport-level protocols exist that can handle either or both cases.)

- The transport level handles end-to-end flow control and data delivery. In practice, only a few transport protocols are needed for most applications. In the Internet, TCP provides reliable, sequenced delivery, whereas UDP provides a datagram service in which data may be lost or delivered out of sequence (both provide a checksum to detect errors so that damaged datagrams are not delivered).

The balance of this section addresses key issues that must be resolved before protocols can be designed for these layers in an advanced MBC system. The number and importance of the subjects that must be addressed reflect the differences between meteor-burst links and other media, and the fact that conventional MBC systems provide only limited networking support.

Addressing. The current standard uses 16-bit addresses, which provide far more address possibilities than any conceivable MBC network is likely to need. However, it may be desirable to reserve a few addresses for special purposes. For example, routing protocols can use a special-purpose address to do any of the following

- Broadcast data to all neighboring nodes

- Broadcast data to all neighboring nodes except one designated node

- Send data to a specific neighbor.

Because of the large address space (in comparison with the likely size of a MBC network), such capabilities can be easily supported and will reduce traffic when multiple neighboring nodes can be reached using the same meteor trail. (In most cases, meteor-trail footprints are so small they will not cover more than one station, but the situation may arise for some mobile applications.) Even when a different trail must be used for each node, such forms of addressing will be useful for network configuration. Addresses can then be assigned when the network is deployed, which can substantially simplify some applications, particularly when military networks have to be deployed on short notice. Many of the addressing problems that occur in large terrestrial networks will not be a problem in an MBC network. With 16-bit addresses, it is feasible to store tables describing each node in an MBC network in what is now a very small amount of memory. This address issue is relevant to all three protocol layers being considered.

51

Exploiting Multiple Paths. As mentioned, message splitting across multiple paths can improve throughput substantially. The current standard, however, does not support this functionality, because sequence numbers are required and messages must be sequential. As a result, one may send the same sequence of messages to multiple nodes, but there is currently no way of splitting a data stream between two or more nodes. Mechanisms to support the splitting of streams to exploit multiple paths are needed for advanced MBC systems at the network level.

Congestion and flow control are unimportant in current MBC systems. Neither congestion nor flow control is a problem for simply passing data between two stations that are directly connected because the link-level flow control is adequate for the low throughputs that in present use. Transport-level flow control can be an issue in principle, but only if an application accepts data at an extremely low rate, which is unlikely. However, congestion and flow control become important in networks with more than two stations. For example, if traffic from several sources is routed though the same station, as shown in Figure 3-30, more capacity may be available for data entering the station than leaving it. Traffic enters station N3 from stations N1 and N2, and is routed to station N4. With sufficient traffic levels and identical link capacities, congestion will thus build up at station N3. As a result, message queues at the station will grow until available memory or buffer space is exhausted. Appropriate flow control and congestion-control mechanisms need to be developed at the network and transport layers if an MBC network is to perform acceptably.
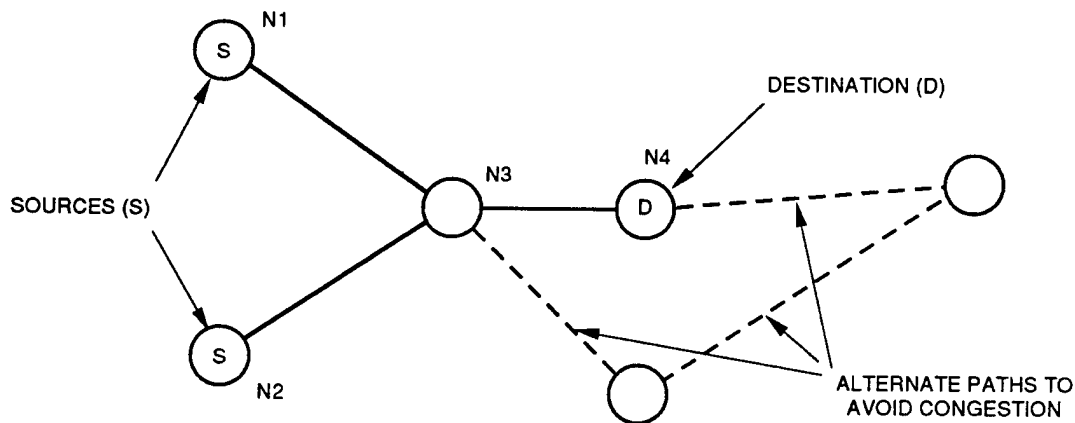
FIGURE 3-30 CONGESTION CAUSED BY INAPPROPRIATE ROUTING

Routing. Our preliminary study of the performance of routing techniques clearly indicates that performance advantages can be gained by choosing the appropriate routing protocol. Various routing techniques are likely to be used in an MBC network:

Shortest-Path Routing. Traffic follows minimal-cost paths to a destination, where the cost of the path may be defined by the number of hops, length of delay, or some other criterion. Typically, a cost is assigned to each link and the cost of the path is the sum of the costs of the links along that path. From any node, there is one shortest path to a destination (Zaumen and Garcia-Luna-Aceves, 1991).

Multipath Routing. Shortest-path routing is not the only possibility; multiple paths to a destination can be used. Paths that are considered must be *feasible* paths, a criterion that, in general, means that the next hop along a path must offer sufficient progress toward the destination

52

to justify consideration. An alternative approach is to compute multiple maximally disjoint paths. Algorithms for computing such paths attempt to minimize the total cost of paths while requiring that the routes share the minimum number of nodes possible for a given topology.

Multicast Routing. In cases where the same messages must be distributed to more than one node, minimal spanning trees can be computed. With branching at intermediate nodes, these provide the lowest-cost paths that will distribute data from a source to multiple destinations.

Many algorithms can be used to implement the above routing techniques. Loop-free routing algorithms are attractive because they avoid sending data along loops, conserving link capacity. On the other hand, some loop-free routing algorithms require additional overhead compared with other algorithms that allow temporary loops to be formed (Zaumen and Garcia-Luna Aceves, 1992). A tradeoff analysis is required to balance the advantages and disadvantages of routing algorithms based on the number of bits expected to be available to control traffic, the size of the MBC networks, and the rate and type of topological changes in the MBC network that can be expected when stations have either fixed or mobile locations. The results of this tradeoff analysis can then be used to design an adaptive routing protocol at the network level.

Transport Mechanisms. A variety of transport-level protocols exist. In the Internet, these include TCP and UDP, reliable datagram protocol (RDP), and versatile message transaction protocol (VMPT) (Bertsekas and Gallager, 1992). RDP guarantees delivery, but not sequential delivery; VMPT was designed to simplify the use of remote procedure call (RPC) and improve its efficiency (Cheriton, 1988). New transport-level protocols, or modification of existing protocols, will be needed for MBC networks, because the operating conditions of such networks, such as timeouts or maximum window sizes, may have to cover a substantially different range than is the case for the networks in which these traditional transport-level protocols are currently used.

A particular concern for an MBC network is the provision of end-to-end acknowledgments at different levels of the protocol stack. These acknowledgments must be generated by the destination because of the characteristics of meteor-burst links. In a typical implementation, an incoming message will be stored in a buffer, which will then be transferred to a higher-level protocol entity. Usually, there is a pool of buffers, and the transport protocol provides each connection with a fixed-size window to store incoming messages (assuming a connection-oriented protocol). If the window fills, typically because either the process using the data has not yet read the currently queued data or because out-of-sequence delivery caused a problem, the new message will be dropped for lack of any place to store it. This action is, of course, independent of the link-level question of whether or not the message was actually transferred over the link. As a result, an end-to-end acknowledgment may be needed, and if so, the link-level acknowledgment is redundant. Given the possible impact on performance of generating an unnecessary end-to-end acknowledgment, some indication of type of service is needed (as will be discussed below).

Header Size and Compression. At each protocol layer, a protocol field in the header determines which upper-level protocol handles the data. The field indicating the number of entities that can be supported in the layer above must be large enough so as not to limit the number of protocols one might reasonably want to implement. For example, the Internet protocol (IP) provides an octet, thereby allowing 256 transport protocols; currently, 99 protocols are supported in terrestrial internetworks, many of which are of little interest for MBC (Reynolds and Postel, 1992); e.g., a packet video protocol is of no use over a meteor-burst channel. Because bits are a scarce resource in MBC networks, it is advisable to limit the number of available transport protocols to those that can support realistic applications of MBC networks. A smaller field allowing up to 64 protocols

would more than likely suffice for an MBC network. It would provide sufficient space for both the transport protocols used by applications and a variety of protocols that may be used for network control and exchange of routing tables. Even if the type and number of protocols and services are tailored for MBC, the size of protocol headers may be too large for the available throughput. If so, header compression may be necessary. Recently, Jacobson (1990) proposed a technique that allows TCP/IP headers to be compressed for transmission over serial links, which reduces headers that typically require 40 bytes to a compressed header that is, on the average, 3 bytes long. The compression algorithm can be implemented in 250 lines of C, and takes about 90 μs to compress or decompress a header using a 20-MHz MC68020 processor (Jacobson, 1990). Compression is possible in this case because many headers share the same fields during a typical TCP session, and only a few connections, on the average, are active at any one time over a low-throughput link. Similar compression techniques may be usable for MBC systems, and further study is needed.

Fragmentation. Splitting a large message into multiple streams at the network layer, with each segment being sent along a different path, can significantly decrease delay and increase throughput when there is no competing traffic. For shorter messages, however, this technique may not work as well. Separate headers would then be needed for each stream and extra data would be needed to control reassembly and to prevent deadlock (the link protocol uses a go-back-n strategy to avoid retransmissions, which does not work if there are supposed to be gaps in the data stream). A tradeoff analysis is necessary to determine the minimum message size for which multipath routing makes sense.

Additional Control Bits in Link Layer. The current Federal meteor-burst standards (Federal Standards 1055 and 1057) break messages up into segments containing 14 octets. With one exception, the standards fit the information needed in a network-level header into a 14-octet segment. The exception occurs when a message can be addressed to multiple stations. An 8-bit field indicates the number of destinations that may be addressed by one message. Subsequent octets contain these addresses (the last one padded with nulls). All the standard internetworking-level message headers contain a 6-bit priority field (the remaining 2 bits are a "port designator" that indicates whether the message is encrypted or not, with three types of encryption supported). The standard assigns priorities 17 to 23 for general use, reserving the values 0 to 16 and 24 to 63 for network control. Although additional investigation is necessary, the number of priorities available for network control seems excessive, based on experience with other network-control protocols (e.g., IP). If the general-use priorities were shifted to 4 to 10, then with priorities 0 to 3 and 11 to 15 available for network control, two bits would be available for other purposes.

Similarly, the message type code (MTC) field currently uses 4 bits from an octet, which also contains a 4-bit last segment count (LSC) field that stores values from 1 to 14. The MTC assigns three values (currently 1, 2, and 8), leaving the rest for network-control purposes for a total of 16 possible codes. If fewer than 16 values are actually needed, extra bits of information can be encoded in the LSC/MTC octet. Table 3-1 shows how many bits are needed to encode the LSC values and some number of MTC values. In this table, if only 9 MTC values are needed, one bit can be used for other purposes. The number actually needed, of course, will require further study. In any case, if fewer than 10 MTC values are needed, the encoding can be implemented efficiently: if only 7 bits are needed to encode all possible LSC/MTC values, a table of length 128 can be used to retrieve the two numbers, with the 7-bit code serving as an index into the table.

In any event, it is highly likely that at least two extra bits can be obtained from the internet-working message header, and possibly more [one from the LSC/MTC code and one or more if the

destination address count (DCT) field requires less than a full octet, given the number of destinations that can be handled by one packet in practice]. With these extra bits, it would be possible to

Table 3-1

MESSAGE-TYPE CODE-BIT UTILIZATION

Number of Codes	Free Bits in Octet
1	4
2	5
3	6
4	6
5	7
...	...
9	7
10	8
...	...
16	8

encode a few type-of-service fields. In addition, because of the available space in the 14-bit standard header, it may be desirable to use the first octet in the first segment following the header. If three bits are available, they can be used to encode the following:

- A type-of-service field to indicate reliable or unreliable delivery at the network level. This controls the use of end-to-end acknowledgments.

- A field indicating how the protocol field is encoded. Options include:

  - No transport protocol, indicating that the network level is used directly by applications (this provides compatibility with existing applications).

  - The transport-protocol field is encoded by using the DCT field (implying that the destination count is 1).

  - The transport-protocol field is the first available octet following the destination list.

3.4.4 Technical Issues for Testing

To develop a networking standard for MBC systems, some experimentation will be necessary so that the design can be validated. These experiments will involve the use of simulation and emulation. Tests using actual MBC hardware would also be desirable, but they are not essential and probably would be prohibitively expensive. Simulations are programs that model a meteor-burst system using any of a variety of methodologies; emulations run fully implemented

55

protocols, but replace some parts of the system with a combination of software and hardware that approximates the behavior of an actual MBC network. Simulations and emulations will provide a sound basis for comparing various possible network-level and transport-level protocols for inclusion in an MBC networking standard. They also provide a cost-effective approach for evaluating design options and for showing that proposed standards can be implemented to assure good performance.

The use of emulation will also provide prototype implementations that can be used by vendors as a starting point for developing full MBC systems that support networking. (Although an emulation will test a usable implementation of a protocol, the best performing implementations of network and transport level protocols are often found to be processor and system dependent because performance is sensitive to buffer management and low-level operations used to process headers.)

Simulation. Simulations can be used to model various aspects of an MBC network. Typically, a simulation will be used to model specific protocols or algorithms and to estimate the impact on performance using a simplified channel model, coupled with a queue-based model for buffering at intermediate nodes. Although approximate, such simulations are far easier to write than the protocol software they model, and are a significant help for investigating design alternatives. Simulations will prove particularly useful in determining which type of routing algorithms to use and in selecting appropriate transport-level capabilities. As one justification for the need for simulations, we should point out that experience with the DoD Internet is not likely to be applicable for determining which protocols to use in an MBC system. For example, at the transport level, performance on the Internet is good enough that TCP and UDP are the protocols in wide use. RDP exists, but is not available at many sites because standard networking applications such as FTP, TELNET, and electronic mail (Email) do not use RDP, and most other applications which frequently run on a local area network (LAN) provide sufficient throughput that TCP or UDP suffices.

UDP is preferable to TCP in cases where the amount of data to send can be conveniently packaged by an application into small messages, occasional (and typically very infrequent) loss of data is acceptable, and a host has to deal with a large number of other hosts concurrently. Most operating systems limit the number of files a process can have open, which complicates the use of TCP when many hosts have to interact intermittently over a long time. RDP or a similar protocol may, however, be appropriate for MBC applications, so performance modeling should be used to evaluate this possibility.

Emulation. Developing an MBC emulation facility will allow networking protocols to be tested realistically because, in an emulation, full implementations of network protocols can be run with the MBC hardware and link-level software modeled by the use of interprocess communication and/or standard networking software running on a high-speed LAN. Typically an emulator runs on a high-performance work station, and the extra processing is used for instrumentation and either for modeling a network or for modeling multiple nodes on the same workstation. Using multiple workstations connected by a LAN makes it possible to model moderately large networks, limited primarily by the baud rate the LAN can support. Such an emulation would require writing software that models the behavior of a meteor-burst channel and models the protocols specified in Federal Standards 1055 or 1057. The software will pass datagrams representing the messages specified in these formats between processes, using either IPC or LAN-based networking software as required.

56

It is possible to have more MBC nodes in a model than workstations, provided that each MBC node is modeled as a separate process, and assuming that the CPU and LAN have adequate performance. It is also possible to run emulations by scaling time so that the software runs much faster than real time. This approach is practical because protocol software is event driven, which can be done using a set of timers. Software implementing these timers can scale time as appropriate. The scaling is particularly easy to do when an implementation of a protocol suite provides a timer module that is used by all the protocols (none of which make system calls for this purpose directly).

Experience indicates that emulators are difficult to build for testing communication software in general. However, the reasons involve speed requirements that are not relevant to MBC. Unlike most networks, an MBC system has its links active for a very short time at widely spaced time intervals. Because events occur on a time scale measured in seconds, constraints specific to an operating system (e.g., process scheduling and IPC bandwidth) are not likely to interfere with the emulation.

In addition to writing the emulation software, we must address several technical issues, as discussed below.

- *Assigning MBC nodes to workstations.* The means by which MBC nodes are allocated to workstations has yet to be determined. If neighboring nodes are placed on the same workstation, the load on the LAN will be reduced, but the contention for processing at the workstation will be increased. On the other hand, if neighboring nodes are put on different workstations, the probability of contention at the workstation is reduced, but the traffic sent over the LAN is increased. A tradeoff analysis must be made based on whether LAN traffic or processing at each workstation is more critical.

- *Validating the emulation.* Ideally, we would like to compare the behavior of an emulation with the performance of an actual MBC network for validation. Although the use of as large a network as practical would be desirable for this purpose, 4 to 10 nodes would suffice. Two nodes would suffice for testing models for individual links.

- *Determining size limits.* There is a limit to the size of the MBC network that can be emulated. This limit can be estimated by emulating a series of small networks in parallel (no connectivity between the networks). At some point, contention will cause the emulation's behavior to diverge from the behavior of the MBC network to be modeled. The point where this divergence happens determines the size of the network we can emulate reliably. Of course, the emulation will have been validated independently for the small networks.

- *Gathering statistics.* Since a LAN is needed to pass emulated MBC traffic between workstations, one would prefer not to use the LAN to pass statistical data to a file server. That chore should be handled either by adding a second LAN, or by placing a disk at each workstation.

3.4.5 Recommendations

We recommend that a networking capability be included in the standards for advanced MBC systems and that the design and testing program described above be carried out.

57

3.5 Mobile Systems

Because a number of past and planned future MBC applications involve links in which at least one station is mobile, it is important to consider how advanced technologies might be used to improve the performance of these systems. The platforms on which mobile systems have been successfully mounted include surface vehicles, ships, and aircraft. In particular, MBC systems have been used to communicate with and monitor the locations of trucks for the long-haul trucking industry as a competitive commercial service offered by the Pegasus Message Corporation and Transtrack, Inc. Also, Larsen et al. (1991) describe the results of a test program and discuss designs that have been used for MBC systems on military surface vehicles. Successful ship-to-shore MBC operations have been demonstrated (MCC, 1979), and MBC operations from aircraft have been demonstrated successfully for many years, starting with an SRI implementation of a system aboard a Navy PBY in 1957 and including the BLOSSUM system for air-to-ground communications currently under development in the United Kingdom (Cannon and Reed, 1987).

In general, none of the MBC propagation effects are of any more importance for mobile than for fixed systems. Because the meteor-trail footprint has dimensions of tens of kilometers, even a high-speed aircraft flying at 600 knots (about 0.3 km/s) will be able to maintain communications for the duration of virtually all meteor trails (average trail lifetime is less than a second) before flying out of the footprint. Also, the Doppler shift caused by the motion of the platform will be on the order of only a few tens of hertz even in extreme cases, so it will have no significant effect on system performance. Likewise, the multipath propagation effects that are important for mobile microwave systems are not a factor for MBC systems. However, the noise and interference environment for mobile systems may sometimes be worse than for fixed stations that are usually sited in specially selected low-noise locations.

The problems important for mobile MBC systems are mostly those caused by the practical difficulty of mounting antennas with adequate gain on platforms that have limited space and may be subjected to extreme mechanical and aerodynamic stresses. Although conformal antenna technologies could help with these problems, the cost benefit ratio would probably be too high to be attractive. In some cases, power for mobile systems is limited also, but advanced technologies are not likely to be of much help (except perhaps in a few cases where improved batteries and/or solar cells can play a role). In general, we assume that mobile systems will have relatively low transmitter power and omnidirectional, low-gain antennas, and so will be functionally comparable to what are considered here as remote (rather than master) stations.

Of course, the advanced technologies already discussed for fixed systems, including better modulations, adaptive data rates, adaptive antennas, and networking, can all be applied to improve the performance of mobile systems. Even if practical constraints do not permit installation of an adaptive antenna array on a mobile platform, using an adaptive array at the other end of the link will still help overall system performance. For example, if vertical polarization must be used for the mobile antenna instead of horizontal, it is of no consequence as long as the master station has the recommended capability for a fully adaptive antenna (that is, with adaptive polarization as well as adaptive beam forming and adaptive nulling).

As mentioned previously, a potential problem with mobile systems could arise when a single meteor-trail footprint contains more than one MBC system. However, a number of solutions for this problem are possible, including assigned time slots for each mobile system to broadcast its acquisition signal and different frequency allocations for different systems.

58

Mobile systems will also require networking support. There are two cases to consider: mobile remotes and mobile master stations. In some respects, the former case is simpler because remote stations do not relay traffic. Routing to mobile stations, however, will require network control algorithms that can maintain tables to indicate which master station (or stations) can be used with a particular remote station. The dynamic nature and variable spatial extent of meteor footprints (Rich et al., 1990) make it especially important to develop network protocols that will deal with resolution of the contention mentioned above between multiple simultaneous signals, when two or more stations are located within a single footprint. As contention resolution will generally be a problem only when stations are separated by 100 km or less, it presumably will arise more often for mobile than for fixed stations. It will also be necessary to manage the transition when a mobile remote station moves into the range of one master station and out of the range of another, a case particularly well suited to multihoming. (Multihoming is a standard technique in the telecommunications industry for dealing with the situation of a user connected to two nodes, perhaps while in transition between them.)

Mobile master stations pose another level of complexity when used as relays because the network will have to be managed with a time-varying topology. Routing algorithms that can handle such topologies exist (Bertsekas and Gallager, 1992; Garcia-Luna-Aceves, 1993), however, algorithm efficiency, particularly with regard to minimizing the number of routing messages needed to respond to a topology change, is a major technical challenge that must be addressed. In addition, if the positions of both stationary and mobile stations in an MBC network are known, it may be possible to develop routing algorithms that can exploit this information. In particular, given the locations and capabilities of all nodes in an MBC system, it will be possible to generate a topology for the network by using propagation models to determine connectivity. Such a topology, however, represents the best connectivity possible and, because of resource limits, a node may have to restrict itself to a subset of the nodes it can physically reach. Algorithms that combine geographic positions for long-distance communications with information about the local topology may be particularly attractive for this case.

It may also be possible to predict the locations of some mobile nodes in advance, either because they are required to follow a particular path, or because they have limited capabilities, and knowledge of their last reported positions allows some inferences about their possible new positions. Algorithms to handle this case need to be developed.

Clearly, knowledge of node positions for mobile systems will be valuable for networking purposes. Although the provision of this information will add cost to the system, such information may also be needed for other purposes, in which case the incremental cost for networking purposes will be negligible. Both LORAN and global positioning satellite (GPS) systems are readily available and can provide more than enough position accuracy for MBC applications. LORAN is a very inexpensive technology, and the cost of GPS receivers is still dropping rapidly.

Finally, algorithms that try to minimize the total amount of traffic (both user traffic and routing-algorithm traffic) in a mobile network have yet to be developed. Research in this area should prove to be particularly fruitful for MBC systems because the propagation medium makes so little capacity available. With a sufficiently mobile network, routing-algorithm traffic itself may cause congestion in the network. On the other hand, if routing-algorithm traffic is too severely limited, user traffic may be misrouted, which also consumes resources. Research is needed to find the optimum traffic balance. One approach might be to exploit the fact that when a mobile station

59

attempts to send a message to a fixed station to which it is not linked directly, the neighboring node actually used for the first link can be included in the header, and this information can then be used by the network in building new routing tables at minimal cost.

4 BASELINE SYSTEM AND ITS TESTING

In this section, the recommendations for the different technology areas presented in Section 3 are brought together to specify a particular implementation of each technology in a prototype version of an advanced MBC system. This prototype advanced system will herein be referred to as the *baseline system*. This baseline system is intended to demonstrate the feasibility of the advanced standard design concept and to evaluate the system performance. This performance will be compared with that of a conventional MBC test system with the same power-aperture product.

4.1 Specifications

We first describe the overall test system and present options for its incremental development in discrete stages. We then describe the simulations and emulations needed to define how the advantages of networking can be made available for advanced MBC systems.

4.1.1 Overall System

The MBC test system will consist of both a conventional system and the baseline system, collocated and configured to operate simultaneously to provide data suitable for detailed performance comparisons. (In other test programs, it has been the practice to record data with different systems on separate occasions and then to assume that conditions were the same on the average, so that the data comparison would be valid.) In our case, however, the signals from the two different systems will propagate simultaneously via the same meteor trail, so it will not be necessary to assume that trail characteristics and noise conditions are equal on the average for data recorded at different times. The baseline and conventional systems will operate from two sites, chosen to be representative of MBC sites and operating conditions in temperate latitudes. The master station will be located in Menlo Park, California, and the remote station will be in Billings, Montana, locations often used in previous MBC experiments. Both the conventional and baseline systems will operate in the full-duplex mode and will generally be unmanned during operation. Because remote stations are often limited in prime power, the operating protocol will require continuous transmission of tone signals from the master station (which is not typically limited in prime power). When the tone signals are received via a meteor trail at the remote station, the two MBC links (conventional and baseline) will be initiated by responses from the remote station.

A block diagram of the master station for the overall system is shown in Figure 4-1. The conventional system will use separate antennas (5-element Yagis, horizontally polarized) for transmitting and receiving, but the baseline system will use duplexers to allow simultaneous transmission and reception on the same antenna. The baseline system antenna will be a 4x4 array of tripole pairs to permit adaptive beam forming, nulling, and polarization control using 48 receiver/ADC units, as described in Section 3.3.4. The transmitting frequencies will be 48.858 and 48.758 MHz for the conventional and baseline systems, respectively, and the respective receiving frequencies will be 46.759 and 46.959 MHz. (These frequencies are close enough together that the meteor scattering and propagation effects and the noise can be considered to be the same for both systems, thus allowing direct comparisons of their measured performances.) A Global Position Satellite (GPS) system will give coordinated universal time (UTC) for all data to be recorded at both the master station and the remote station. As defined in the current Proposed Federal Standard 1055, the modulation for the conventional system will be DBPSK, whereas the baseline system will use
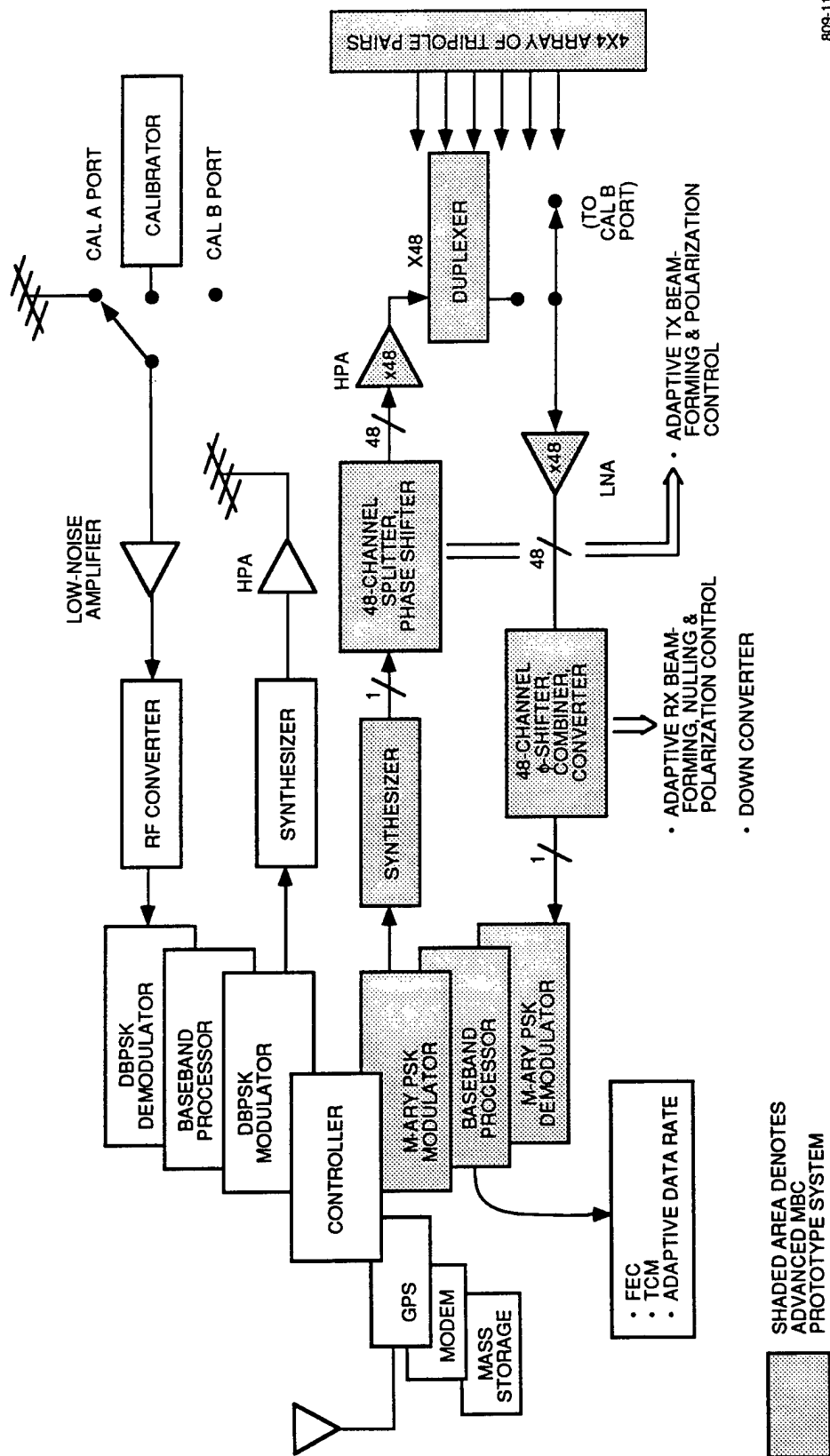
61

FIGURE 4-1 MASTER STATION FOR THE OVERALL TEST SYSTEM

62

adaptive M-ary PSK with ARQ-FEC and adaptive TCM, as discussed in Sections 3.1.4 and 3.2.4. Magneto-optical disks will be used for data recording, and a modem will be used both for data transfer to other computers for off-line analysis and for remote monitoring and control of the unmanned system.

Figure 4-2 shows a block diagram for the remote station. In this case, separate 5-element Yagis are used as transmitting and receiving antennas for both the conventional and baseline systems, although one Yagi is shared for receiving by the two systems. (The two receiving frequencies are 100 kHz apart; thus, the Yagi gain will be effectively the same for both frequencies.) Aside from the differences related to the use of simple Yagi antennas at the remote station for the baseline system, the features at the remote station are much the same as those shown previously for the master station.

Among the many functions to be performed by the controllers at the master and remote stations shown in Figures 4-1 and 4-2 will be to initiate data recording whenever either or both the conventional and baseline systems establish a link via a meteor trail. Presumably, in most cases, the two systems will automatically respond to their probe signals' reflections from a particular trail. However, in some cases, one of the systems may not detect its probe, and data will be needed for performance comparison even if one data set shows no signal present.

A crucial requirement for achieving meaningful test results is that the power-aperture product $(P_T G_T G_R)$ be the same in both propagation directions for both the conventional and baseline systems. Only by meeting this requirement will the performance comparisons reflect the benefits of the advanced technologies instead of a simple brute-force advantage of one system over the other. Thus, the transmitter power at each end of the path will be reduced as necessary to offset the larger antenna gain of the array for the baseline system. This normalization of power-aperture product will be achieved during operation as described below. While the master station is broadcasting probe signals seeking a suitable meteor trail, both systems will transmit 500 W, but the baseline system will use only a single turnstile pair from the array as its transmitting antenna. Although a Yagi forms a beam and a turnstile pair has an azimuthally omnidirectional pattern, the gains of the two antennas are both about 11 dBi, so the power-aperture products can be considered to be the same for both systems. When the remote station receives the probe signal, the baseline remote transmitter will reduce its power by 12 dB (the gain of the 4×4 array) below the 500 W of the conventional remote transmitter. When the baseline master station then continues its transmission using the full 4×4 array, it will also need to reduce the power output of each of its amplifiers by 12 dB to offset the array gain. This drastic reduction of P_T for the baseline system is essential for a valid comparison of its performance with that of the conventional system. In some cases, the full power of the baseline system can be used to show that the measured throughput increases as expected, but the data for these cases should not be compared with the conventional system data.

4.1.2 Options for Incremental Development

Three stages of incremental development are described here to provide some flexibility in program planning. These stages all involve different sizes for the baseline system antenna array.

A minimal baseline test system would have a single tripole pair for its antenna. This first stage of development would thus not include any of the adaptive antenna features, but would permit

63
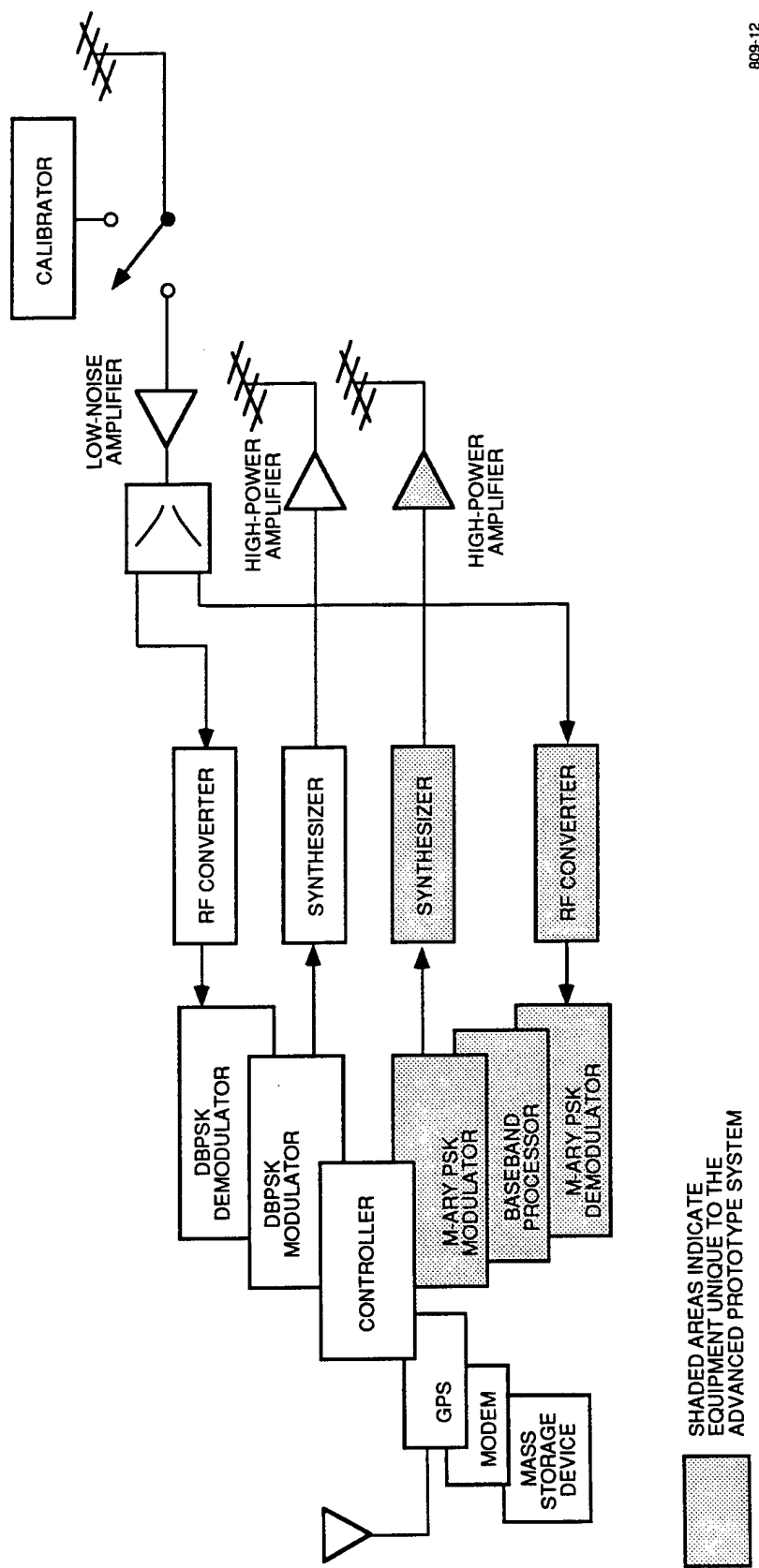
FIGURE FIGURE 4-2   REMOTE STATION FOR THE OVERALL TEST SYSTEM

SHADED AREAS INDICATE
EQUIPMENT UNIQUE TO THE
ADVANCED PROTOTYPE SYSTEM

809-12

64

testing of the advanced modulation concept, including adaptive data rates, ARQ-FEC, and adaptive TCM using M-ary PSK as the underlying modulation. In this case, 500-W transmitters would be used at both the master and remote stations and would not need any adjustment to normalize the power-aperture product because the gains of the Yagi antennas and of the tripole pair are all about 11 dBi.

We propose using DSP techniques and hardware to implement the modulator, demodulator, and error correcting sections of the baseline system. The modulator and error correction encoding sofware will be implemented in a DSP processor and its associated digital-to-analog converters (DACs). The processor's firmware will modulate the data using TCM M-ary PSK, depending upon the SNR at each instant of the trail. Both the algorithm to perform the M-ary PSK modulation and the algorithm to perform the convolutional encoding will be implemented on the DSP. Optionally, one of the available VLSI implementations of convolutional encoders may be used prior to the DSP, lowering the processing requirements of the DSP itself.

The demodulator and error correction system used in the receiver will also employ a DSP to perform key functions. The initial demodulation of the M-ary PSK modulation will be performed on a DSP processor. It will pass soft-demodulated decisions to a Viterbi decoder which will perform the error correction. In this case, the complexity of the Vidterbi decoder, necessary to demodulate the TCM M-ary PSK, dictates the complexity of the dedicated DSP processor for that function alone. We may also use a VLSI implementation of the soft-decision Viterbi decoder, which is commonly available.

A minimal adaptive antenna, consisting of a 2×2 array of tripole pairs, could be added to the system for the second stage of development. All the necessary additional amplifiers, receivers, ADCs, and adaptive control hardware and software would also be included. In this case, 6 dB of power reduction would be needed to offset the increased antenna gain of the 2×2 array compared with the Yagi antennas of the conventional system.

A prototype operational antenna could then be achieved by expanding to the 4×4 array described previously as the third and final stage of development. Any actual operational version of an advanced MBC system would be designed with an array size that would be optimized by the tradeoff between P_T and $G_T G_R$, but it is unlikely that more than 16 elements will be used for most MBC applications.

Table 4-1 lists specifications for the critical components that make up the baseline and conventional systems in these various stages of development.

4.1.3 Networking Simulation and Emulation

It is not considered practical to deploy prototype versions of the advanced baseline MBC system at enough sites to permit testing of the networking architecture and protocols using actual MBC systems in on-the-air operation. Thus, the networking part of the development and testing of a baseline system, and the eventual drafting of proposed Federal standards for advanced MBC networking, should be done using simulations and emulations. In this context, simulations are computer programs that model the performance of an individual MBC station, and emulations run fully implemented networking protocols for a collection of these simulated stations. The models of individual station performance may be empirical or theoretical, or some combination of the two.

Possible empirical models for different stations might be constructed from the data recorded at approximately the same time on successive days, using the baseline and conventional test systems described above.

Table 4-1

ADVANCED MBC BASELINE AND TEST SYSTEMS

Component	Conventional System	Advanced Baseline System		
		Minimal Version	With Minimal Adaptive Antenna	Overall System
Transmit Antenna	5-element Yagi	Tripole Pair	2×2×2 Tripole array	4×4×2 Tripole array
G_T	11 dBi	11 dBi	17 dBi	23 dBi
Receive Antenna	5-element Yagi	Tripole Pair	2×2×2 Tripole array	4×4×2 Tripole array
G_R	11 dBi	11 dBi	17 dBi	23 dBi
Duplexer	No	Yes	Yes	Yes
Adaptive Antenna	No	No	Yes	Yes
Modulation	DBPSK	ATCM M-ary PSK	ATCM M-ary PSK	ATCM M-ary PSK
P_T per Element	500 W	500 W	~ 30 W	~ 8 W
P_T Total	500 W	500 W	125 W	~ 30 W
Transmitter Frequency	48.858 MHz	48.758 MHz	48.758 MHz	48.758 MHz
Receiver Frequency	46.759 MHz	46.959 MHz	46.959 MHz	46.959 MHz

Functionally, the networking architecture will be similar to the Open System Interconnection (OSI) architecture developed by the International Standards Organization (ISO) or to the Department of Defense (DoD) architecture, but the protocols will need to be modified to reflect the limitations of MBC systems, such as the relatively low bit rates and long response times. For example, the Internet protocol (IP) has an 8-bit time-to-live field which limits the time over which an IP datagram may exist to 255 s, which is probably too short for an MBC network. The field measures time in seconds, but will be decremented by each router even if the router processes the datagram in a fraction of a second. Although the OSI and DoD protocol stacks contain a large number of protocols at various levels, we will need to concentrate on the network and transport

levels (OSI Levels 3 and 4). For example, in the case of the transport-level protocols, a protocol like reliable datagram protocol (RDP) may be quite useful because it does not need to deal with sequential delivery.

The emulator will consist of the appropriate software running on high-performance workstations connected by a high-speed LAN. Because of the high speed of workstations compared with what is needed for MBC applications, each workstation will be capable of modeling multiple MBC nodes. Four or five workstations, each with a 400-Mbyte disk for logging outputs and for swapping, will probably be required to model a good-sized MBC network. An ethernet bridge will also be required, primarily so that software and the standard operating system can be stored on a file server and so that network traffic generated by other users does not interact with traffic generated by the MBC models. The software will pass datagrams representing the messages specified in the appropriate formats between the simulated MBC terminals, using either interprocess communication (IPC) or LAN-based networking software as required.

It will be possible to run emulations by scaling time so that the software runs much faster than real time, perhaps using a set of timers. Timers are practical because protocol software will be event driven. Software implementing these timers can scale time as desired, which is easy to do when an implementation of a protocol suite provides a timer module that is used by all the protocols (none of which make system calls for this purpose directly).

The networking standards will have to define service access points and primitives in addition to message formats, a critical requirement because of the need for software interface specifications in a layered architecture.

4.2 Testing

In the testing program, the data to be recorded at both the master and remote stations for both the conventional and baseline systems include date, UTC to the nearest microsecond, SNR as a function of UTC, and the noise level in decibel-watts per hertz (dBW/Hz). In addition, at the master station, the antenna beam steer direction (azimuth and elevation), null positions, and polarization, all as a function of UTC, will be recorded for the baseline system. Raw data from the baseline system ADCs will be recorded as well as the processed data at both the master and remote stations. Enough around-the-clock operations should be conducted in all seasons to give good definitions of system performance under all relevant conditions and for all types of meteor trails. If the system is developed in stages as described above, this full measure of testing should be carried out at each stage.

To test the effectiveness of advanced modulations and adaptive data rate technologies, we will perform both single technique tests and integrated tests. The tests will compare the conventional system, employing the Federal Standard 1055 technologies—8 kb/s, DBPSK modulation—to the advanced baseline system, running in parallel. In the initial stages of testing, we will examine the performance gain of techniques on their own merit. We will start by using QPSK and comparing the performance to the conventional system. We will then perform individual tests of QPSK-TCM and adaptive M-ary PSK. The results of these tests will show the relative performance increase due to these separate techniques solely. We will then perform a test of the integrated system, testing ATCM, which combines both the advanced modulation and the adaptive data rate techniques from Section 3.

The analysis of the data will define the value of the throughput for each system, as well as their relative value, both under all conditions and as a function of time of day, day of the year, and channel characteristics. By also processing the raw data offline without including adaptive polarization and comparing the output with the original result, the quantitative value of this feature (adaptive polarization) can be assessed. Likewise, the values of ARQ, FEC, and adaptive TCM can be measured and their cost effectiveness can be determined in a similar manner.

5 SUGGESTED PROGRAM PLAN

The objective of this study is to provide the information needed to successfully define Federal standards and to permit the orderly development of the next generation of MBC systems. This next-generation system is referred to here as an *Advanced MBC System*, and is essentially the same as current MBC systems, except that it will be configured to take full advantage of the enormous signal-processing capabilities made possible by modern DSP hardware and software.

Today, DSP processors have become fast enough and powerful enough to replace many typical analog circuits used in communication systems. Digital signal processors can perform such processes as filtering, signal generation and signal demodulation in the discrete time domain, using specific algorithms implemented in firmware. This adds great flexibility to typical communication systems, because, now, changes can be made in software instead of modifying the hardware. For instance, the design of a variable filter in the analog domain can be complicated and costly; however, using DSPs we can implement adaptive filters using only the processor, an ADC, and a DAC. The ADC translates analog signals into digital data, which the processor can use to perform the filtering algorithm. The processor then sends the digital results to the DAC, where it is translated back into an analog signal. If the filter requires a change in parameters, no parts have to be added or replaced, we need only to change the DSP's firmware. Similarly, we can implement functions such as signal generation using the same hardware. DSP systems can implement complex modulators, such as our proposed ATCM system. The software controlling the processors can use tables to generate complex waveforms. They can also perform functions such as convolutional coding through the use of logic operations and circular buffers.

This study has identified the appropriate technologies that should be allowed a role in the development of new MBC systems: advanced modulations, adaptive data rates, adaptive antennas, and networking. Also, specifications have been written for a prototype advanced baseline system that includes implementation of each of these technologies. Plans have been described for testing this baseline system to characterize its performance and to verify the soundness of the design concept.

Here, we outline a number of program elements that together will lead to a first draft for the new Federal standards. These program elements can be carried out either in series or in parallel depending on the availability of funding and the schedule requirements for issuing the new standards. The program elements are listed in the order in which they should be completed, and are described below. They could be carried out one at a time in series, or any number of them could be combined (as long as the priority sequence is maintained) to hasten the completion of the program. The suggested program elements are: (1) establish a conventional MBC test system based upon the proposed Federal Standards 1055, 1056 and 1057; (2) include the recommended advanced modulation with adaptive data rates, error-correction coding, and other components needed to create a minimal advanced baseline system, then collect and analyze data to evaluate system performance; (3) include a minimal adaptive antenna and collect and analyze data; (4) expand the adaptive antenna array to its full size and collect and analyze data; (5) perform the recommended simulations and emulations to develop the appropriate MBC networking protocols and write a draft of the proposed standards to guide their implementation; (6) and write the first draft of the remainder of the proposed new Federal standards. Further discussion of these program elements is given below.

Basic Conventional Test System. A basic conventional test system should be established as described in Section 4 with the master station in Menlo Park, California, and the remote station in Billings, Montana. The performance of this conventional system will serve as a standard for comparison with the performance of the advanced baseline system. The two systems will be collocated and will share some components. DBPSK will be the modulation, and 5-element Yagi antennas will be used at both the master and remote stations. The conventional system will operate simultaneously and in parallel with the advanced baseline system, making it possible to compare system performance on each individual meteor trail. The digitized receiver output will be recorded at both the master station and the remote station for off-line analysis.

Minimal Advanced Test System. M-ary PSK, with M varying in powers of two from 4 to 16, should be added to the baseline system as the recommended advanced modulation along with the necessary software for real-time adaptive control of the data rate. The recommended ARQ-FEC capability should also be included. The baseline master station antenna will be a single tripole pair with a fixed feed system for one receiver and one transmitter for the pair. The transmitter will have an output power of 500 W, the same as the conventional system, so that $P_TG_TG_R$ is the same for both systems. Data should be gathered for a statistical evaluation of the relative performance (throughput) achieved with the both the conventional and baseline systems. Sufficient data will be recorded and analyzed to characterize performance for all types of meteor trails. For this purpose, we will record data continuously, for several days, during different seasons. Although we expect the results to confirm the well-known diurnal and seasonal effects, the primary reason for this extensive sampling is to ensure that our database is representative of all types of trails under all conditions.

Minimal Adaptive Antenna. The antenna for the advanced system should be increased to a 2×2 array of tripole pairs at the master station, and a separate receiver and transmitter should be included for each of the 12 dipole pairs to permit full adaptivity in beam steering, nulling, and polarization for both transmitting and receiving. Again, sufficient data will be recorded and analyzed to characterize performance under all conditions.

Larger Adaptive Antenna. The 2×2 array described above should be enlarged to 4×4 with the appropriate additional receivers and transmitters to give a power-aperture product comparable to that expected for a typical operational system, as was described in Section 4. As before, sufficient data will be recorded and analyzed to characterize performance under all conditions.

Networking. The recommended networking protocols should be designed and tested with computer simulations and emulations of an MBC network. (We assume that it will not be practical to deploy enough stations to test the protocols with a network of actual MBC stations.) The results of these tests will be used to write proposed networking standards for the advanced MBC system.

New Standards. The results of the above tasks should be used to prepare the first draft of the proposed Federal standards for an advanced MBC system. These new proposed standards will follow the formats of the existing proposed Federal Standards 1055, 1056, and 1057, with an entirely new standard drafted to define the networking architecture and protocols (as part of the program element described above).

The baseline system has been defined in this study through the inclusion of results from the industry survey, literature survey and technology simulations. Testing of the baseline system will

provide the basis for developing the advanced standards. These standards will provide for an orderly development of advanced MBC systems and will allow for the incorporation of the broad range of technological advances which have occurred since the definition of the proposed Federal Standards 1055, 1056 and 1057. Industry and manufacturing comment will also be included in the advanced standards to provide interoperability between MBC equipment. Because the baseline system will have been adequately and thoroughly tested in both the laboratory and field environments, the completeness of the advanced standards can be ensured.

The schedule for completing these program elements and the subsequent draft of the advanced standards will depend on whether they are independent sequential elements or are combined to some extent. If the new standards are not needed for several years, each program element could be accomplished in turn, over as long as a year. On the other hand, a maximally parallel program could probably be completed in as little as two years, or perhaps less, if the need is urgent.

6 REFERENCES

Abel, Martin W., "Meteor Burst Communications: Bits per Burst Performance Bounds," *IEEE Transactions on Communications*, Vol. **COM-34**, No. 9 (September 1986).

Al-Jabri, A.K., "Coding and Interleaving for Meteor-Burst Communications," *Electronics Letters*, Vol. **26**, No. 22, pp. 1907-1909 (October 25, 1990).

Ames, John W., "STRATSEC Transportable Shore Node — Link Design for the VHF Meteor-Burst Broadcast Relay Element," Technical Report T2-4, Contract N00039-81-C-0086, SRI International, Menlo Park, CA (January 1984).

Berlekamp, Elwyn R., Robert E. Peile, and Stephen P. Pope, "The Application of Error Control to Communications," *IEEE Communications Magazine*, Vol. **25**, No. 4, pp 44-57 (April 1987).

Bertsekas, D., *Linear Network Optimization*, MIT Press, Cambridge, MA (1991).

Bertsekas, D., and R. Gallager, *Data Networks*, Second Edition, Prentice Hall Inc., Englewood Cliffs, NJ (1992).

Braun, R.M., and G.J. Meyerowitz, "Investigations into Adaptive Rate Modems for Meteor Burst Communications," *Electronics and Communications Engineering Journal*, pp. 213-222 (October 1991).

Brayer, Kenneth, and Subramaniam Natarajan, "An Investigation of ARQ and Hybrid FEC-ARQ on an Experimental High Latitude Meteor Burst Channel," *Proc. IEEE MILCOM*, Section 15.6.1, pp. 313-319 (October 1988).

Brown, D.W., "Faraday Rotation in Meteor Burst Communication," *Proc IEEE MILCOM* (1991).

Cannon, P.S., "Polarization Rotation in Meteor Burst Communications Systems," *Radio Science*, Vol. **22**, No. 3, pp.500-510 (1986).

Cannon, P.S., and A.P.C. Reed, "The evolution of meteor burst communications systems," *J. IERE*, Vol. **57**, No. 3, pp. 101-112 (1987).

Chang, Sheldon S. L., and Donald L. Schilling, "Efficient Communications Using the Meteor-Burst Channel," *IEEE Transactions on Communications*, Vol. **40**, No. 1, pp. 119-128 (January 1992).

Cheriton, David, "VMTP: Versatile Message Transaction Protocol," Network Working Group RFC 1045 (1988).

Cohen, David, William Grant, and Francis Steele, NTIA Report 89-241, Meteor Burst System Communications Compatibility, U.S. Department of Commerce, National Telecommunications and Information Administration, Washington, D.C. (1989).

Compton, R.T., Jr., "The Tripole Antenna: An Adaptive Array with Full Polarization Flexibility," *IEEE Transactions on Antennas and Propagation*, Vol. **AP-29**, no.6 (November 1981).

Compton, R.T., Jr., *Adaptive Antennas — Concepts and Performance*, Prentice Hall, Englewood Cliffs, NJ (1988).

Crane, Peter C., "An Empirical Analysis of the Application of Forward Error Correction to Meteor Burst Communication," *Proc. IEEE MILCOM*, Section 14.3.1, pp. 249-254 (October 1988).

Datasheet 5530, Datapro Information Services Group, McGraw-Hill, Inc. (1992).

Edwards, Gwyn, *The Forward Error Correction Handbook*, Stanford Telecommunications, Inc., Santa Clara, California (July 1990).

Frederick, T. J., M.A. Belkerdid, and M. Georgiopoulos, "Error Control Coding For Meteor Burst Channels," *Proc. IEEE MILCOM*, Section 43.6.1, pp. 1033-1036 (1991).

Garcia-Luna-Aceves, J.J., "Loop-Free Routing Using Diffusing Computations," *IEEE/ACM Transactions on Networking*, Vol. **1**, No. 1, to be published.

Heilman, Paul M., Michael M. Murray, Mark J. Rich, and Bernadette Yetso, "Meteor Burst and Space Diversity Testing — Phase III," Final Technical Report, GE/RCA Purchase Order 939202-0001-73, SRI International, Menlo Park, CA (July 1989).

Hirst, G.C., H.C. Maddocks, D.M. Morgenstern, C.J. Pitts, and M.P. Scheidt, "Adaptive Meteor Burst Communications Network," FY85 Year-End Report, MITRE Corporation, Bedford, MA (1985).

Jacobson, V., "Compressing TCP/IP Headers for Low-Speed Serial Links," Network Working Group RFC 1144 (1990).

Jacobsmeyer, Jay M., "Adaptive Trellis Coded Modulation for Band-Limited Meteor Burst Channels," *IEEE Journal on Selected Areas in Communications*, Vol. **10**, No. 3 (April 1992).

Keiser, Bernhard E., *Broadband Coding, Modulation, and Transmission Engineering*, 477 pages, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1989).

Kokjer, K.J., and T.D. Roberts, "Networked Meteor-Burst Data Communications," *IEEE Communications Magazine*, Vol. **24**, No. 11 (November 1986).

Larsen, J.D., R.S. Mawrey, and F.L. Anderson, "Military Vehicle Communication via Meteor Burst," *Proc. IEEE MILCOM*, pp. 705-710 (1991).

Larsen, J. D., R. S. Mawrey, and J. A. Weitzen, "The Use of Antenna Beam Steering to Improve the Performance of Meteor Burst Communications Systems," *Proc. IEEE MILCOM* (October 11-14, 1992).

Larsen, J. D., S. W. Melville, and R. S. Mawrey, "Adaptive Data Rate Capacity of Meteor Burst Communications," *Proc. IEEE MILCOM*, Sect. 40.1.1, pp. 0863-0867 (1990).

Lee, Edward A., and David G. Messerschmit, *Digital Communication*, Kluwer Academic Publishers, Boston (1988).

Mathis, James E., J.J. Garcia-Luna-Aceves, Mark G. Lewis, and Bruce Sifford, "SINCGARS Packet Switch Overlay," Final Report for the U.S. Army, Contract DAAB07-85-C-K581, SRI International, Menlo Park, CA (1986).

Mawrey, R. S., J. D. Larsen, and J. A. Weitzen, "Conversational Voice Communication Over a High Performance Meteor Burst Channel," *Proc IEEE MILCOM*, San Diego (October 11-14, 1992).

MCC, "Meteor Burst Communications Link Demonstrations Test (Test and Evaluation ID No. K734)," AD B041326, prepared by Meteor Communications Consultants, Kent, Washington, for U.S. Naval Electronics Systems Command, PME-108, NC1, Crystal City, Arlington, VA (1979).

Morin, Stephen J., "A Comparison of Digital Modulation Techniques for Meteor Burst Communications," *Proc IEEE MILCOM*, (May 1987).

Mui, Shou Y., "Coding for Meteor Burst Communications," *IEEE Transactions on Communications*, Vol. **39**, No. 5, pp. 647-652 (May 1991).

Murota, Kazuaki, and Kenkichi Hirade, "GMSK Modulation for Digital Mobile Radio Telephony," *IEEE Transactions on Communications*, Vol. **COM-29** (July 1981).

Nes, H., "Meteor Burst Polarization Trails," *Electronics Letters*, Vol. **21**, No. 24, pp. 1132-1133 (1985).

Pasupathy, Subbarayan, "Minimum Shift Keying: A Spectrally Efficient Modulation," *IEEE Communications Magazine*, Vol. **17**, No. 4 (July 1979).

Proakis, John G., *Digital Communications*, McGraw-Hill Book Company, New York (1989).

Pursley, Michael B., and Stuart D. Sandberg, "Variable-Rate Hybrid ARQ for Meteor-Burst Communications," *IEEE Transactions on Communications*, Vol. **40**, No. 1, pp. 60-73 (January 1992).

Qualcomm, "Q0256 K=7 Multi-code Rate Viterbi Decoder," Technical Data Sheet, Qualcomm Inc., San Diego, California (December 1991).

Reynolds, J., and J. Postel, "Assigned Numbers," Network Working Group RFC 1340 (1992).

Rich, Mark J., Paul M. Heilman, Michael M. Murray, and Bernadette Yetso, "Experimental Investigation of Meteor Burst Footprints," AGARD Electromagnetic-Wave Propagation Panel Symposium, Crete, Greece (September 1990).

SAIC, "Meteor Burst Improvement Study," Final Report for DARPA (Ronald Bauman), Science Applications International Corporation, Marlborough, MA 01752 (11 February 1992).

Schanker, John Z., Meteor Burst Communications, Artech House, Boston/London (1990).

Schilling, D.L., T. Apelewicz, G.R. Lomp, M. Dyer, L. Lundberg, F. Rogers, and J. Woodhouse, "The FAVR Meteor Burst Communications Experiment," *Proc. IEEE MILCOM*, Sect. 31.1.1, pp. 0683-0687 (1991).

Skolnik, M.I., and D.D. King, "Self-Phasing Array Antennas," *IEEE Transactions on Antennas and Propagation*, Vol. **AP-12**, pp. 142-149 (March 1964).

Tannenbaum, A., *Computer Networks*, Prentice Hall, Inc., Englewood Cliffs, NJ (1981).

Viterbi, Andrew J., et al., "A Pragmatic Approach to Trellis Coded Modulation," *IEEE Communications Magazine* (July 1989).

Zaumen, William T., and J. J. Garcia-Luna-Aceves, "Dynamics of Shortest-Path Routing Algorithms," *ACM Computer Communication Review*, Vol. **21**, No. 4, pp. 31-42 (September 1991).